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Original Article

Utilization of a cloud-based radiology analytics platform to monitor imaging volumes at a large tertiary center

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ABSTRACT

Rationale and objective: In this study, we evaluate the ability of a novel cloud-based radiology analytics platform to continuously monitor imaging volumes at a large tertiary center following institutional protocol and policy changes.

Materials and methods: We evaluated response to environmental factors through the lens of the COVID-19 pandemic. Analysis involved 11 CT/18 MR imaging systems at a large tertiary center. A vendor neutral, cloud-based analytics tool (CBRAP) was used to retrospectively collect information via DICOM headers on imaging exams between Oct. 2019 to Aug. 2021. Exams were stratified by modality (CT or MRI) and organized by body region. Pre-pandemic scan volumes (Oct 2019-Feb. 2010) were compared with volumes during/after two waves of COVID-19 in Illinois (Mar. to May 2020 & Oct. to Dec. 2020) using a t-test or Mann-Whitney U test.

Results: The CBRAP was able to analyze 169,530 CT and 110,837 MR images, providing a detailed snapshot of baseline and post-pandemic CT and MR imaging across the radiology enterprise at our tertiary center. The CBRAP allowed for further subdivision in its reporting, showing monthly trends in average scan volumes specifically in the head, abdomen, spine, MSK, thorax, neck, GU system, or breast.

Conclusion: The CBRAP retrieved data for 300,000 + imaging exams across multiple modalities at a large tertiary center in a highly populated, urban environment. The ability to analyze large imaging volumes across multiple waves of COVID-19 and evaluate quality-improvement endeavors/imaging protocol changes displays the usefulness of the CBRAP as an advanced imaging analytics tool.

1. Introduction

Cost pressure for medical imaging is rapidly rising in the setting of emerging imaging technologies and variability in health care utilization after the COVID-19 pandemic [1]. Thus, it is vital for radiology services to collect imaging metrics to maximize scan efficiency/volume while providing high quality care to patients. Oftentimes, process improvement in radiology is based on approaches used in business strategy, including the Plan, Do, Study, and Act cycle (PDSA), six sigma technique (focus on improving quality and reducing variation to decrease defects and save money), and the lean approach (differentiating process steps in the imaging workflow that add value by affecting medical care decisions and eliminating those that do not) [1–4].

Continuous monitoring of process improvement strategies is certainly crucial in radiology, especially in the setting of major extrinsic/environment events. The 2020 COVID-19 pandemic is an example of such an event– it impacted radiology enterprises across the United States in unprecedented ways, dramatically reducing imaging utilization while overwhelming intensive care units throughout the country [5,6]. Resulting government restrictions/policy changes at

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Abbreviations: CT, Computed tomography; MRI, Magnetic resonance imaging; CBRAP, Cloud-based analytics tool; MSK, Musculoskeletal; HEENT, Head, eyes, ear, nose, throat; GU, Genitourinary.

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medical institutions improved death and hospitalization rates after the first COVID-19 wave and enhanced preparedness against a second COVID-19 wave from October to December 2020 and onwards into 2021 [7,8]. In addition, monitoring of imaging would be useful to identify areas within a radiology service that need continued refinement (e.g., long imaging exam durations or inefficient transition time between scans), therefore improving staffing planning and resource allotment.

Clearly, evaluating institutional trends in radiology is essential to optimize imaging utilization while simultaneously providing the highest possible quality of examination services [9]. However, monitoring a radiology enterprise can be challenging at large hospitals, where the large number of imaging exams as well as the complexity of various modalities is difficult to track. Previous studies evaluating processes in sectional imaging—e.g. computed tomography (CT) and magnetic resonance imaging (MRI)—have been limited by small sample size or are entirely simulation-based [4, 9, 10].

Thus, the overall goal of this study was to evaluate the ability of a novel cloud-based radiology analytics platform (CBRAP) to continuously monitor imaging volumes at our large tertiary center radiology enterprise following institutional protocol and policy changes. Through the lens of the COVID-19 pandemic, we collect data to monitor trends in monthly scan volumes from 29 CT and MRI systems at a large tertiary center from October 2019 to August 2021 [11]. We hypothesize that this tool can evaluate scanner utilization on a large-scale, allowing assessment of policy changes following extrinsic factors such as a pandemic lockdown.

2. Material and methods

This study was approved by the local Institutional Review Board and was deemed exempt from patient informed consent requirements because it used deidentified data and did not involve human subjects' research.

2.1. Data source: cloud-based analytics tool

The CBRAP (teamplay, Siemens Healthineers, Germany) (Fig. 1) is a vendor neutral, cloud-based radiology analytics platform relying on a "receiver" software that is installed on a local network to establish communication between hospital systems and the CBRAP servers. The CBRAP receiver acts as the gateway between clinical archives that house radiologic imaging data, (e.g. vendor neutral image archive, VNA) and the CBRAP digital health platform. The HIPAA-compliant CBRAP receiver software processes pseudonymized patient data from DICOM files–direct patient identifiers such as patient name or the original patient ID are not needed for data analysis and therefore not processed. The receiver then uploads the pseudonymized data to the CBRAP digital health platform in the cloud, where they are stored and processed by the respective CBRAP applications [12]. Predefined DICOM tags allow for comprehensive data collection regarding imaging protocol usage, exam volume and duration, radiation dose levels, and patient change times between exams from the image DICOM header (if minimization of uploaded patient data is desired, individual DICOM tag can be individually selected for upload) [11]. This data is relevant for the CBRAP's functionality, and can be used to evaluate trends in radiology service usage and modality usage by a centralized analytics platform [9].

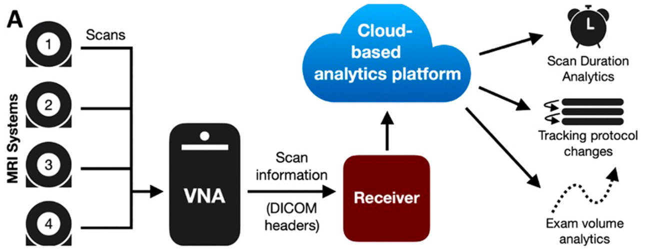

Fig. 1. (use color)– Schematic illustration of data flow in CBRAP. All imaging modalities (11 CT, 18 MRI) send imaging data to a central vender neutral achieve (VNA) which is queried by CBRAP to extract information on daily scan volumes and exam information (e.g. body region, etc.) for each modality. CBRAP: cloud-based analytics tool.

2.2. Study population and organization

Using CBRAP, scan information was retrospectively collected from 29 imaging systems at a large tertiary center from October 2019 to August 2021. This included 11 CT scanners (2 Definition AS, 1 Definition AS+, 1 Definition Edge, 2 Somatom Force, 1 Somatom X, 3 Somatom Drive, 1 Siemens Dual Source Definition) and 18 MRI systems (4 Avanto, 2 Verio, 3 Espree, 3 Skyra, 2 Vida, 2 Sola, 2 Aera, 1 Biograph (Siemens Healthineers, Erlangen, AG). Imaging data collected included monthly number of exams, imaging protocol and body part imaged, and CT or MRI scanner name/location via DICOM headers on each scan.

Patient exams were then stratified by modality (CT or MRI), and total imaging volumes per month for each modality were recorded. A comprehensive list of all CT and MRI protocols was evaluated, and various body part categories deemed to be representative of all imaging protocols were created by an independent observer (SC). For CT imaging, these categories consisted of head, spine, neck, thorax, abdomen, and musculoskeletal (MSK). For MR imaging, categories included head (brain), head/eyes/ears/nose/throat (HEENT) & neck, thorax, breast, abdomen, and genitourinary (GU). Subsequently, scans were manually attributed to a certain body part category based on protocol name (e.g., "CT chest" was categorized as a "thorax" exam). For patients who received imaging exams covering multiple body regions, scans were counted towards each respective body area imaged (e.g., a CT abdomen/chest exam was recorded in both the "abdomen" and "thorax" groups). Body part groups were created with regard to the referring clinician (e.g. an orbital CT was categorized as "HEENT" while CT brain was placed in "head" even though both images involved a similar body area.

2.3. Exclusion criteria

The methodology for inclusion and exclusion of MR/CT exams is detailed in Fig. 2. 1) Exams which did not involve patients, such as test or calibration scans, were excluded. After inspecting a list of all imaging protocols included in the study, a search was conducted to find and exclude all protocols with the keywords "daily," "special," and/or "unspecified." 2) For statistical analysis of scan volumes by body part imaged, exams with missing body part information (e.g., non-specific or missing protocol names) were also excluded.

2.4. Statistical analysis

To assess the effect of COVID-19 on NMH scan volumes, we compared "total" and "by body part" CT/MRI volumes before, during, and after each wave of COVID-19 cases in Illinois (March 2020 - May 2020 and October 2020 – December 2020) (Fig. 3). First, scan volumes for each respective wave were compared against pre-pandemic volumes (October 2019 – February 2020). Percent drops in monthly scan volume during COVID-19 peaks (April 2020 and November 2020) versus pre-pandemic volumes were also calculated. This was done by comparing scan volumes in the month immediately preceding the first wave versus the peak month itself (e.g., for the first COVID-19 wave, the month immediately prior to the first wave (February 2020) was compared with the peak of the wave (April 2020)). Second, to evaluate the extent of post-wave recovery of CT/MR imaging, we compared pre-pandemic scan volumes with the monthly volume between the first and second waves (June 2020 – September 2020) and the scan volumes following the second wave (January 2021 – August 2021). The distributions of scan volume data were assessed with the Shapiro-wilk test, comparisons between groups were made with a t-test or Mann Whitney U test. All statistical analysis was done using SPSS Statistics version 20 (International Business Machines Corporation, New York, USA) and Excel version 16.54 (Microsoft Corporation, Washington, USA).

3. Results

To examine the efficacy of the CBRAP in collecting radiology scan information, data from 169,530 CT and 110,837 MR images were retrieved by the CBRAP across multiple modalities. 8061 calibration scans were excluded (MR:345, CT:7716), leaving a total of 161,814 CT and 110,492 MR scans spanning from October 2019 to August 2021 for analysis (Fig. 2). Specifically for analysis by body part, 2 MR scanners failed to record protocol names in the DICOM header, so they could not be organized by body part scanned. For this reason, an additional 29 CT and 9056 MRI scans were excluded, leaving 161,785 CT and 101,436 MR scans for analysis by body part.

The CBRAP was able to provide a detailed snapshot of baseline CT and MR imaging across the radiology enterprise at our tertiary center. Before the pandemic began, a monthly average of 7316 CT and 5036 MR scans were performed. The CBRAP allowed for further subdivision in its reporting, showing monthly average scan volumes specifically in the head, abdomen, spine, MSK, thorax, neck, GU system, or breast. All results are shown in Table 1 and Fig. 4.

Compared to pre-pandemic months (October 2019 to February 2020), the first COVID-19 wave from March to May 2020 resulted in a substantial drop in total CT (−43 %, 7316 vs. 4622 scans, $p < 0.005$) and MRI (−67 %, 5036 vs. 2403, $p = 0.01$) scan volumes, respectively. For CT scans, spine and MSK applications experienced the greatest reduction (−62 %, $p = 0.005$ and −58 %, $p = 0.005$), followed by CT neck (−45 %, $p = 0.006$), abdomen (−44 %, $p = <0.005$), thorax (−43 %, $p = 0.05$), and brain (−36 %, $p < 0.005$). MR imaging experienced an even more severe decline than CT with MSK imaging experiencing the greatest reduction (−84 %, $p = 0.02$). This was followed by thorax (−79 %, $p = 0.02$), GU (−78 %, $p = 0.02$), spine (−71 %, $p = 0.02$), abdomen (−71 %, $p = 0.01$), breast (−67 %, $p < 0.005$), HEENT & neck (−65 %, $p < 0.005$), and brain (−51 %, $p < 0.005$).

Between the 1st and 2nd COVID-19 waves from May 2020 to October 2020, total CT imaging volumes returned to volumes seen in pre-pandemic months ($p = 0.86$). Monthly CT scan volumes after the first COVID-19 wave also did not significantly differ from pre-pandemic amounts when organized by body part: brain ($p = 0.57$), abdomen ($p = 0.30$), spine ($p = 0.29$), MSK ($p = 0.47$), thorax ($p = 0.27$), neck ($p = 0.17$). For MRI exams, results were similar. In the months after the

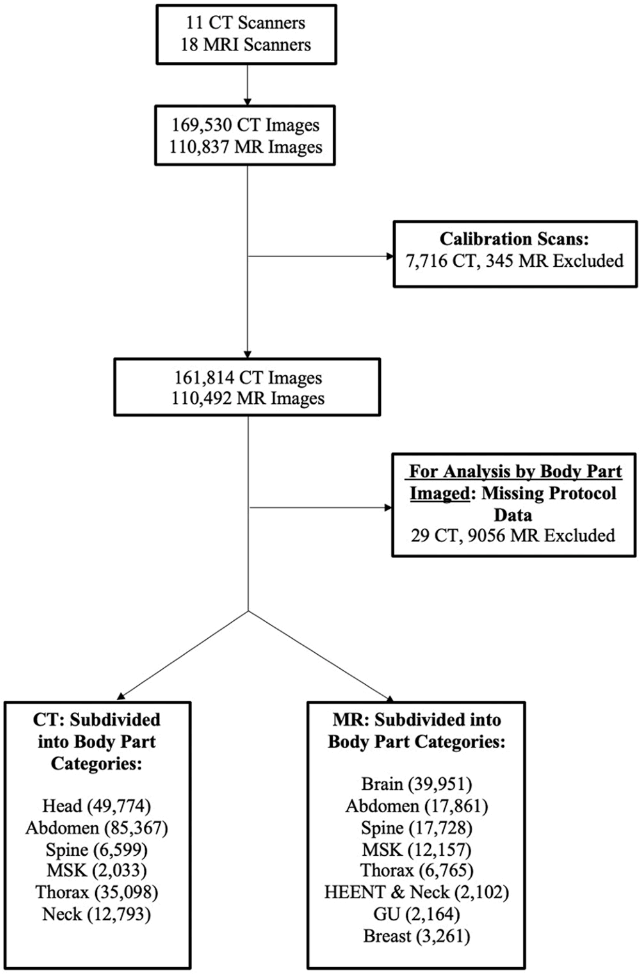

Fig. 2. Flowchart detailing methodology for inclusion & exclusion of MR/CT scans. For analysis of trends in overall scan volumes, 161,814 CT and 110,492 MR images were included. However, only 161,785 CT and 101,436 MR images were included in analysis of changes in scan volumes by body part imaged (since the DICOM header for 29 CT and 9056 MR exams did not include a protocol name identifying the body part imaged). CT: computed tomography. MR: magnetic resonance. MSK: musculoskeletal. HEENT: head, eyes, ears, nose, throat.

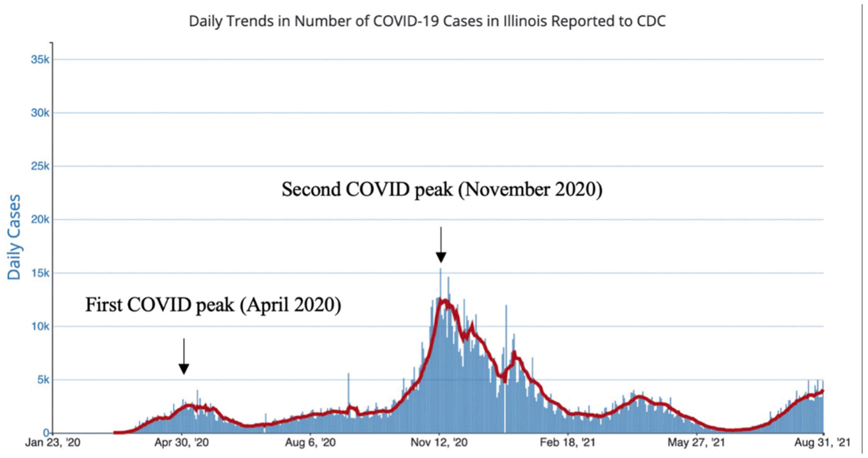

Fig. 3. Number of new daily cases in Illinois from Jan 2020 to Aug 2021 with first and second COVID-19 peaks (peaking at 2565 and 12,381 daily cases, respectively) labeled. U.S. Department of Health & Human Services. CDC Covid Data tracker. Centers for Disease Control and Prevention. https://covid.cdc.gov/covid-data-tracker/#trends_ dailycases.

Table 1
To test the efficacy of the CBRAP, CT and MR mean monthly scan volumes were compared (overall & by body part) between pre-pandemic months (10/19–2/20) versus 1) during the 1st COVID-19 wave (3/20–5/20), 2) between the 1st and 2nd wave (6/20–9/20), 3) the 2nd COVID-19 wave (10/20–12/20) and 4) after the 2nd wave (1/21–8/21). *P < 0.05. CT: computed tomography. MR: magnetic resonance. CBRAP: cloud-based radiology analytics platform.

Parameter	Pre-pandemic (reference)	1st wave (p compared to reference)	Post-1st wave	2nd wave	Post-2nd wave
CT					
Overall	7316 ± 662	4622 ± 575**(p < 0.005)***	7383 ± 391(p = 0.86)	7150 ± 458 (p = 0.69)	7547 ± 867(p = 0.60)
Head	2293 ± 274	1460 ± 131 **(p < 0.005)***	2207 ± 152 (p = 0.57)	2114 ± 117 (p = 0.39)	2344 ± 328 (p = 0.77)
Abdomen	3740 ± 297	2447 ± 316 **(p < 0.005)***	3914 ± 150 (p = 0.30)	3925 ± 323 (p = 0.46)	3986 ± 368 (p = 0.22)
Spine	332 ± 81	149 ± 40 **(p = 0.005)***	283 ± 42 (p = 0.29)	311 ± 61 (p = 0.69)	302 ± 45 (p = 0.47)
MSK	106 ± 35	45 ± 13 **(p = 0.01)***	93 ± 16 (p = 0.47)	82 ± 5 (p = 0.79)	94 ± 17 (p = 0.59)
Thorax	1583 ± 81	1050 ± 119 **(p = 0.005)***	1637 ± 51 (p = 0.27)	1586 ± 69 (p = 0.96)	1590 ± 179 (p = 0.93)
Neck	536 ± 50	341 ± 53 **(p = 0.006)***	582 ± 38 (p = 0.17)	608 ± 35 (p = 0.06)	617 ± 80 **(p = 0.048)***
MR					
Overall	5036 ± 360	2403 ± 678 **(p = 0.01)***	5129 ± 191 (p = 0.64)	5193 ± 463 (p = 0.64)	5250 ± 605 (p = 0.44)
Brain	1795 ± 195	1030 ± 119 **(p < 0.005)***	1870 ± 121 (p = 0.51)	1839 ± 135 (p = 0.72)	1860 ± 200 (p = 0.58)
Abdomen	823 ± 71	371 ± 120 **(p = 0.01)***	834 ± 49 (p = 0.80)	855 ± 73 (p = 0.59)	840 ± 92 (p = 0.72)
Spine	803 ± 47	364 ± 124 **(p = 0.02)***	801 ± 76 (p = 0.98)	854 ± 91 (p = 0.44)	857 ± 148 (p = 0.24)
MSK	600 ± 51	214 ± 115 **(p = 0.02)***	563 ± 22 (p = 0.20)	555 ± 68 (p = 0.39)	575 ± 72 (p = 0.47)
Thorax	294 ± 27	117 ± 52 **(p = 0.02)***	323 ± 33 (p = 0.22)	334 ± 43 (p = 0.24)	331 ± 39 (p = 0.07)
HEENT & Neck	96 ± 9	40 ± 10 **(p < 0.005)***	91 ± 20 (p = 0.66)	96 ± 9 (p = 0.53)	104 ± 15 (p = 0.31)
GU	109 ± 10	43 ± 19 **(p = 0.02)***	84 ± 8 **(p < 0.005)***	107 ± 7 (p = 0.72)	105 ± 8 (p = 0.42)
Breast	140 ± 15	61 ± 17 **(p < 0.005)***	137 ± 13 (p = 0.71)	151 ± 31 (p = 0.61)	172 ± 35 **(p = 0.048)***

first-COVID-19 wave, total MRI scan volumes quickly returned to pre-pandemic levels (p = 0.64) as did monthly MRI exams organized by body part: brain (p = 0.51), abdominal (p = 0.80), spine (p = 0.98), MSK (p = 0.20), thorax (p = 0.22), HEENT & neck (p = 0.66), breast (p = 0.71). Mean monthly MRI GU exams remained reduced (pre-pandemic: 109 vs. post-1st COVID-19 wave: 84, p < 0.005).

The second COVID-19 wave from October 2020 to December 2020 had a much less pronounced effect (−12 % change compared to −43 % during the first COVID wave) and did not significantly reduce total CT scan volumes compared to the three pre-pandemic months (p = 0.69). Similar effects were seen for CT scans organized by body region (p > 0.05). Total MRI scan volumes (−12 % change compared to −67 % during the first COVID wave) and monthly MRI exams organized by body region were maintained on a much higher level with no significant differences compared to the three pre-pandemic months (Fig. 4 C, p > 0.05).

During the period after the second COVID-19 wave (December 2020 to August 2021), total monthly CT and MRI volumes returned to pre-pandemic levels (p > 0.05). After the second wave, mean monthly CT neck and MR breast scan volumes showed a significant increase when compared with pre-pandemic values (536 vs. 617 scans, p < 0.05 and 140 vs. 172 scans, p < 0.05, respectively).

There was a decrease in monthly MR and CT scan volumes in February 2021. We speculate that this was likely caused by three severe weather days in Chicago with temperatures below − 15° to − 20° Celsius along with February being the shortest month of the year (Fig. 4).

4. Discussion

The CBRAP was successful in evaluating more than 300,000 imaging exams across multiple modalities at a large tertiary center. The platform was able to provide detailed data regarding scan volumes – including the specific body part protocols used – as seen in Table 1 and Fig. 4.

Many efforts for process improvement within radiology have been reported. These analyses often center on approaches used in business strategy, including the Plan, Do, Study, and Act cycle, six sigma technique, and the lean approach [1–4]. For example, Beker et. al. employed two research physicians to collect workflow data from two outpatient MR scanners over two weeks, personally recording length of each imaging exam. In doing so, IV/port placement was identified as a source of imaging delay with the highest frequency, while joint injection of contrast medium for MRI arthrography accounted for the delay with the greatest impact on time [13].

Using the PDSA workflow, Recht et. al. utilized various members of the MR imaging department (technologists, nurses, schedulers, physicians, and administrators) to track all aspects of patient flow through the department, from scheduling to examination interpretation, over the course of 3 weeks. [14]. This was to improve total MRI volumes and greater adherence to allotted time slots for imaging exams [14].

Such studies are limited by the painstaking process of data collection, in which researchers/physicians must physically be next to a scanner every day for the duration of the study period to record scan volumes and durations. Because of this, investigations into process improvement have involved small numbers of scanners, limited analysis for multiple imaging modalities, and short measurement phases. For example, a measurement period of 10 days is unlikely to provide a representative snapshot of a radiology enterprise [13]. Thus, the CBRAP used in this

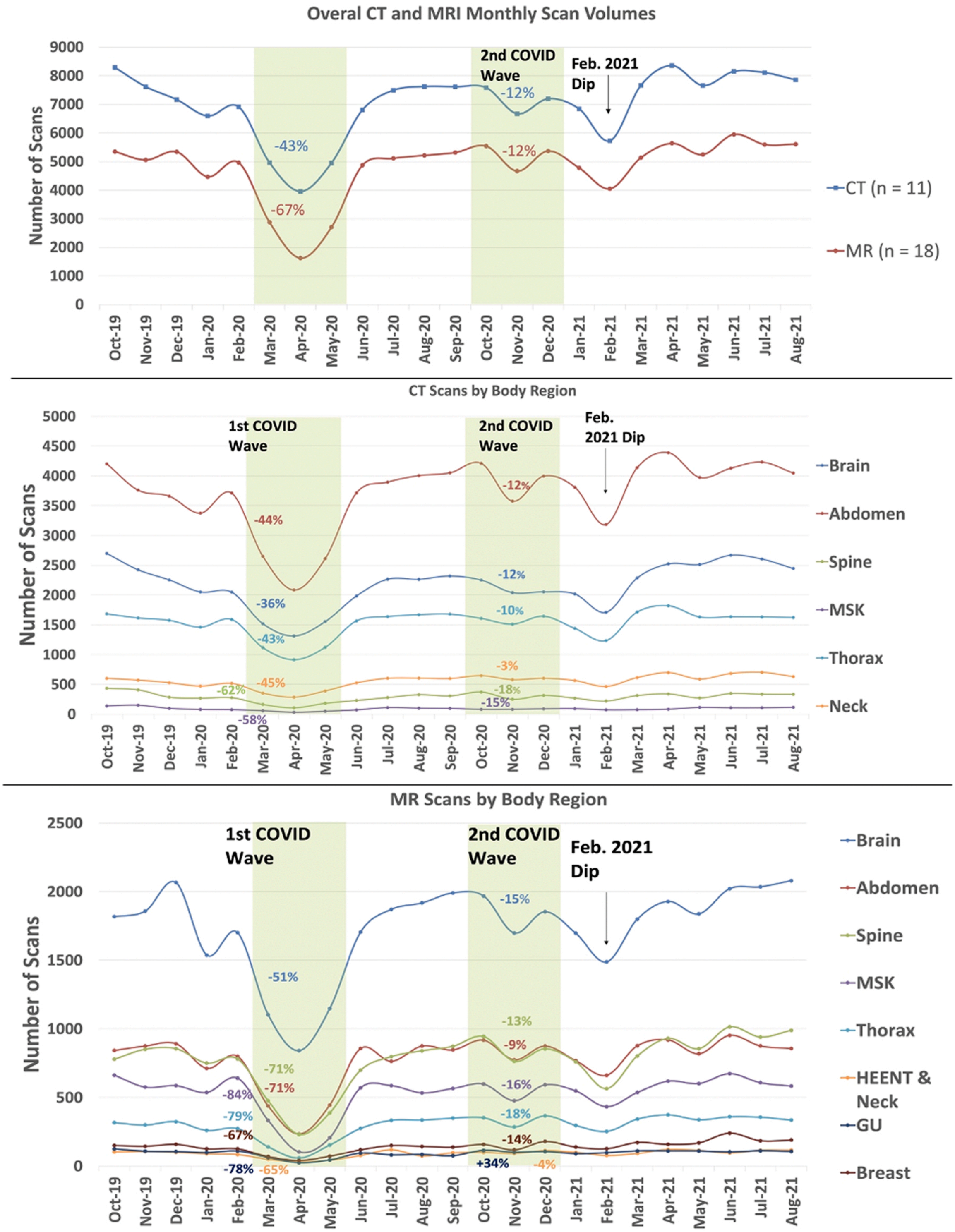

Fig. 4. (use color)– To display the ability of the CBRAP to collect detailed data regarding scan volumes organized by body part: A) Monthly CT and MRI patient volumes including the percent drop in volume from Feb to Apr 20 and Oct to Dec 20. B) The monthly patient volumes for CT and C) MRI categorized by body region, including the percent drop in patient volume for each category during COVID-19 waves. COVID-19: coronavirus-2019.

study is a potential software solution that can access scan archives and store/analyze scan data on a macro level, offering a full scale analysis of a radiology enterprise [2, 3, 15, 16].

Previous methods for process improvement were also insufficient for responding to the unprecedented challenges posed by the COVID-19 pandemic. Beyond its negative effects on streamlining patient throughput and imaging volume, the disruptions caused by the pandemic –whether due to renouncing of care or decreased access—led to increased mortality and poorer clinical outcomes [17]. For example, imaging volume for cancer screening decreased, as did exams for stroke evaluation and diagnosis of appendicitis, sigmoiditis, and renal colic [18]. Considering the above implications on patient care, it is vital that accurate, up-to-date data regarding the impact of environmental events on 1) medical imaging volumes and 2) the efficacy of subsequent institutional policy changes is available. CBRAP provided such information in a detailed and continuously updated manner, identifying significant drops in CT/MRI volumes following nationwide stay-at-home orders and reduction of non-emergent procedures at hospitals. After this first wave, however, imaging volumes returned to pre-pandemic levels and remained stable throughout the second wave and beyond. This is likely due to various nationwide and institution-specific policy changes:

On a national level, the CARES act passed at the end of March 2020 provided $100 billion to hospitals in the US, increasing financial resources for overwhelmed hospitals with intensive care units at full capacity [19]. At the institutional level, hospitals began requiring COVID-19 symptom screening before entry, secondary screening at the radiology front desk, and real-time polymerase chain reaction COVID-19 testing before radiological procedures [20]. Standardized personal protective equipment policies, patient room droplet precautions and imaging suite cleaning protocols were also implemented. From an imaging service distribution standpoint, high-risk/immunocompromised patients with active/suspected COVID-19 infection scheduled for time-sensitive imaging were treated, while other patients went to outpatient imaging centers [20]. Guidelines for specific imaging protocols have also been published. For example, the Society for Cardiovascular Magnetic Resonance published specific recommendations for cardiac imaging for suspected/positive COVID-19 infection (e.g., a short protocol (10–15 min) including a minimum data set of cardiac function and focal myocardial damage) [21]. Chest CT guidelines also surfaced, specifically to aid in the management of patients with severe COVID-19 complications, such as pneumonia or acute respiratory distress syndrome [22,23].

Specifically at our large tertiary center, such changes are reflected in COVID-19 symptomatic screening upon arrival to the hospital in both inpatient and outpatient settings. Both COVID-19 positive and presumed COVID-19 positive patients were assigned to specific “holding areas” away from patients in the general waiting room. All radiology scanners were sanitized between patients. In the setting of aerosol generating procedures such as open tracheal suctioning and nasal bi-pap masks, CT and MRI suites were allowed to ventilate for 70 min [24].

These guidelines for improving COVID-19 preparedness provided a streamlined approach for patient (whether suspicious for COVID-19 or not) to be efficiently evaluated, and they appear to be effective. In the three months following the first wave (June to September 2020), CT and MRI scans had recovered to pre-pandemic levels. Similarly, Chen et. al. reported near complete recovery of breast and prostate cancer screening (−3.8 % and +4.1 %) by July 2020 (compared to July 2019), while other investigators even reported a rebound in scan volume by June 2020 [25,26]. In our study, MRI GU exams were the exception as they remained significantly decreased during this post-1st wave period. By the second COVID-19 wave and beyond, total and monthly (by body part) CT and MRI volumes were only moderately reduced and did not significantly differ from pre-pandemic volumes. In fact, mean monthly CT neck and MR breast exams in 2021 exceeded their pre-pandemic volumes.

Real time monitoring of imaging DICOM data is possible with a DICOM viewer, but would be labor intensive. Moreover, data collection from the CBRAP is standardized and performance is likely higher in the cloud-based approach. Clearly, the CBRAP has potential for numerous radiological applications—not only to assess response to potential future COVID-19 waves, but to quickly evaluate the efficacy of quality-improvement projects, imaging protocol/workflow changes and/or identify areas within the radiology service that need continued refinement (e.g., long imaging exam durations or inefficient transition time between scans), improving staffing planning and resource allotment.

This CBRAP has already been successfully employed for analysis of radiology workflows. For example, Meyl et. al. used the tool to investigate the effect of MRI coil exchanges on delays in 7184 exam changeover times [9]. In addition, Maguire et. al. has also utilized our CBRAP for evaluation of CT radiation dosage on a more frequent basis to optimize future studies [15]. Continued areas for refinements in terms of imaging policy, efficiency, and quality must be systematically identified to meet today’s ever-changing health care demands. Future studies are needed to assess the CBRAP’s preface in a commercial and/or clinical setting, for example regarding its ability to isolate specific imaging protocols of interest and collect data regarding image exam duration/transition time. Nonetheless, our results display the usefulness of the CBRAP as an advanced imaging analytics tool.

4.1. Limitations

Our study is limited by its retrospective character and data from a single institution. Regarding the analysis of imaging during COVID-19, there are many confounding factors not considered in this study that undoubtedly affect scan volumes: severity of disease over time in the study region, reduced COVID-19 restrictions in mid-to-late 2021, fluctuating level of patient concern regarding exposure risk, impact of the economic downturn, and varying ability of hospitals to respond to the pent-up demand for imaging [27]. Moreover, 29 CT and 9056 MRI scans were excluded from analysis of scan volumes by body part (9085 out of the 272,306 CT and MR scans included for analysis of total scan volumes), accounting for 3 % of images included in this study. While these exclusions are unlikely to alter the general trends of the data, they may impact certain body part specific exams more than others, and thus introduce some bias into these analyses.

5. Conclusion

The CBRAP was successful in evaluating more than 300,000 imaging exams across multiple modalities at a large tertiary center in a highly populated, urban environment. The CBRAP’s ability to analyze large imaging volumes across multiple waves of COVID-19 suggests its versatility and effectiveness to monitor exam characteristics such as volume and duration.

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Ethical statement

This study did not include human subjects.

CRediT authorship contribution statement

Stanley Chu: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Mitchell Collins:** Writing – review & editing. **Maurice Pradella:** Conceptualization, Writing – review & editing. **Martin Kramer:** Software, Writing – review & editing. **Rachel Davids:** Writing – review & editing. **Mathis Zimmerman:** Writing – review & editing. **Sarah Fopma:** Writing – review & editing. **Alexander Korutz:** Writing – review & editing. **Blair Faber:** Writing – review & editing. **Ryan Avery:** Writing – review & editing. **James Carr:** Supervision, Project administration. **Bradley D. Allen:** Supervision, Project administration, Writing – review & editing. **Michael Markl:** Supervision, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Martin Kramer: Employee – Siemens Healthineers, Rachel Davids: Employee – Siemens Healthineers Mathis Zimmerman: Employee – Siemens Healthineers, Bradley D. Allen: Consultant – Circle Cardiovascular Imaging, Michael Markl: Research Support—Siemens Healthineers, Research Grant – Circle Cardiovascular Imaging, Research Grant –

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