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Original Investigation

Impact of COVID-19 Pandemic on the Workload of Diagnostic Radiology: A 2-Year Observational Study in a Tertiary Referral Hospital

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Rationale and Objectives: To evaluate the impact of COVID-19 pandemic on diagnostic imaging workload in a tertiary referral hospital.

Materials and Methods: Radiological examinations performed in pre-pandemic period (2015-2019) and in pandemic period (2020-2021) were retrospectively included. Based on epidemiological data and restriction measures, four pandemic waves were identified. For each of them, the relative change (RC) in workload was calculated and compared to the 5-year averaged workload in the corresponding pre-COVID-19 periods. Workload variations were also assessed according to technique (radiographs, CT, MRI, ultrasounds), body district (chest, abdomen, breast, musculoskeletal, head/neck, brain/spine, cardiovascular) and care setting (inpatient, outpatient, emergency imaging, pre-admission imaging).

Results: A total of 1384380 examinations were included. In 2020 imaging workload decreased (RC = -11%) compared to the average of the previous 5 years, while in 2021 only a minimal variation (RC = +1%) was observed. During first wave, workload was reduced for all modalities, body regions and types of care setting (RC from -86% to -10%), except for CT (RC = +3%). In subsequent waves, workload increased only for CT (mean RC = +18%) and, regarding body districts, for breast (mean RC = +23%) and cardiovascular imaging (mean RC = +23%). For all other categories, a workload comparable to pre-pandemic period was almost only restored in the fourth wave. In all pandemics periods workload decrease was mainly due to reduced outpatient activity ($p < 0.001$), while inpatient and emergency imaging was increased ($p < 0.001$).

Conclusion: Evaluating imaging workload changes throughout COVID-19 pandemic helps to understand the response dynamics of radiological services and to improve institutional preparedness to face extreme contingency.

Key Words: Radiology; Diagnostic imaging; Workload; COVID-19; Pandemics.

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Abbreviations: COVID-19 coronavirus disease 2019, **SARS-CoV-2** severe acute respiratory syndrome coronavirus 2, **ED** emergency department, **XR** radiography, **CT** computed tomography, **MRI** magnetic resonance imaging, **US** ultrasound, **RC** relative change

INTRODUCTION

Coronavirus disease 2019 (COVID-19) is a highly contagious infectious disease caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (1). The first case was identified in China at the end of December 2019, but it rapidly spread worldwide, being declared a pandemic by the World Health Organization on March 11, 2020 (2). Among the European countries, Italy has been the first to experience the SARS-COV-2 spread at the end of February 2020, with the Lombardy region at the epicenter of the pandemic (3). In March 2022, the confirmed COVID-19 cases in Italy exceeded 13 million, of which about 18% were in Lombardy (4).

Due to the high contagiousness of the virus, many governments declared a state of national emergency (5) issuing national lockdowns, social distancing, and mandatory vaccination against SARS-CoV-2 (6,7). Also, to accommodate the overwhelming number of patients with COVID-19-like symptoms, healthcare institutions have undergone a deep

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reorganization with the redeployment of people and resources, especially in acute general medicine and critical care (8−10). Specific measures to prevent infection transmission were introduced as well, including dedicated pathways for COVID-19-positive patients, mandatory use of personal protection equipment, physical distancing when possible, and encouraging remote working and follow-up visits (11,12). Screening programs and non-urgent elective examinations and medical procedures were postponed (13,14), while ED visits for disorders other than COVID-19 dropped, also due to the patients' fear of contracting the virus in the hospital environment (15).

These changes had a drastic impact on the activities of radiology departments, influencing the quantity and type of examinations performed every day in the clinical practice. As shown in several studies (16−19), the pandemic caused a reduction in the total imaging volume, but with relevant differences depending on the imaging modality and the examined body region. However, to the best of knowledge, most of these studies evaluated the change in radiological workload during the COVID-19 pandemic focusing only on its first wave. In the following outbreaks, other factors have come into play, such as improved security protocols, increased availability of healthcare resources, loosening of the restrictions, reduced patient concern for infection, pent-up demand for postponed imaging, and gradual increase in vaccination coverage (17). How these variables have affected the activities of radiology departments and the recovery rate to pre-pandemic examination volumes still need to be established.

In this study, the impact of the COVID-19 pandemic on the radiology workload in a tertiary referral hospital was analyzed, providing a comparison with the pre-pandemic period and offering insight into the dynamics behind the changes that diagnostic imaging activities experienced between 2020 and 2021.

MATERIALS AND METHODS

Study Design and Setting

This was an observational retrospective study designed following the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guideline (20) as applicable.

The study was conducted in Niguarda Hospital, a tertiary referral hospital in Milan, Northern Italy, which is a hub for emergency medicine, adult traumas, oncological and cardiovascular diseases, neurovascular and body interventional radiology, and general and transplant surgery. The center was also designated as a COVID-19 hub throughout the entire pandemic, being in an area that experienced early onset of COVID-19 and a high incidence of cases compared to the rest of the country.

All diagnostic examinations performed in the Radiology and Neuroradiology Departments from January 1, 2015 to December 31, 2021 were retrospectively included. Nuclear medicine imaging, imaging for radiation therapy planning, and intra-operative imaging for surgical and/or interventional radiology procedures were not considered. All data related to the imaging examinations were queried and retrieved using the institutional Radiology Information System (MedRIS Elefante system/Impax, AGFA Healthcare System, Mortsel, Belgium).

The study was performed in line with the principles of the Declaration of Helsinki and was approved by the Local Ethics Committee (decision number: 188-22042020). Since data were collected retrospectively in aggregated form without including patient images, informed consent was waived.

Definition of Time Periods

The period from January 1, 2015 to December 31, 2019 was defined as pre-pandemic period, while the period from January 1, 2020 to December 31, 2021 was defined as pandemic period. In the latter range, based on government epidemiological data and restriction measures (4,21,22), four COVID-19 pandemic waves were identified (Figure 1): first wave (March-May 2020), second wave (October-December 2020), third wave (March-May 2021) and fourth wave (October-December 2021). During the first wave a complete national lockdown was imposed halting all non-essential businesses and limiting free movement; most outpatient and elective healthcare services were suspended as well. In the second and third waves, restrictions were similar but with a stringency level based on a system of regional tiers assigned after periodical assessment of the epidemiological risk. Hospitals were expanded to have larger capacity for beds and intensive units than in the first wave, but outpatient and elective services were still reduced to a varying extent. Moreover, during the third wave social and healthcare workers had already received complete vaccination against COVID-19, while the vaccination of elderly and frail people was ongoing, In the fourth wave most of the population was fully vaccinated and restrictions were much looser, mainly concerning unvaccinated or partially vaccinated people.

This made it possible to maintain outpatient and elective healthcare services with only marginal reductions.

Data Analysis

For each year and each pandemic wave, the total number of examinations (i.e., the imaging workload) were collected and grouped into different categories according to imaging modality (radiography (XR), computed tomography (CT), magnetic resonance imaging (MRI), ultrasound (US)), body region (chest, abdomen, breast, musculoskeletal, head/neck, brain/spine, cardiovascular) and care setting (inpatient, outpatient, emergency imaging, pre-admission imaging).

To improve the robustness of subsequent analyses, the mean, minimum and maximum values of imaging workload over the five pre-pandemic years were calculated and used for comparisons.

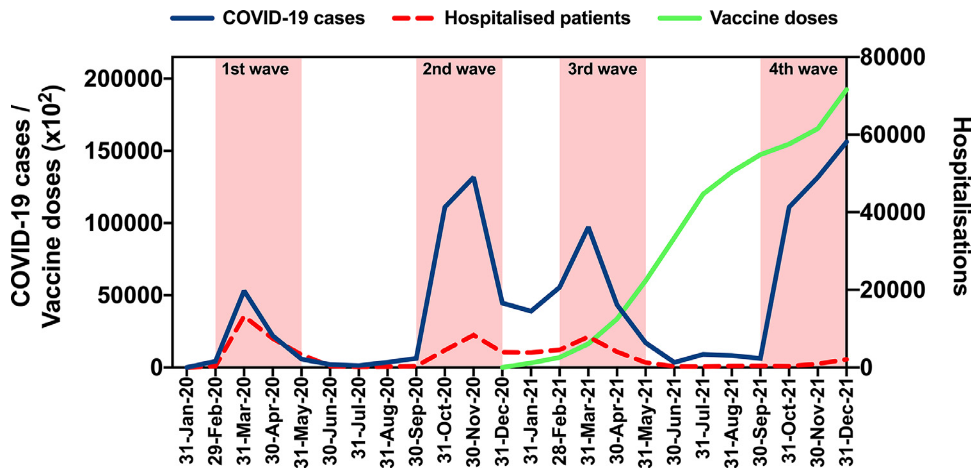

Figure 1. Definition of the four pandemic waves: time periods included in the red areas were identified as pandemic waves based on epidemiological data and restriction measures. Trends of COVID-19 cases, hospitalization of COVID-19 patients and vaccine dose administrations in Lombardy region are also reported. (Color version of figure is available online.)

Pre-pandemic and pandemic periods were compared in terms of overall annual workload and then focusing on the four pandemic waves as defined above. Variations in overall workload and by imaging modality, body region and care setting were reported as relative change (RC) taking the 5-year averaged pre-pandemic workload as reference. RC from the 5-year minimum and maximum pre-pandemic workload was considered as well. Specifically, in case of a pandemic workload below the minimum or above the maximum over the five pre-pandemic years the change was considered relevant, otherwise slight.

Moreover, statistically significant differences in the workload distribution (in proportion to the total workload) between different care setting categories were assessed using the chi-squared test with post hoc analysis of adjusted residuals (23).

An analogue sub-analysis was performed focusing on chest XR and chest CT, namely the reference imaging techniques for the diagnosis and management of COVID-19 patients and thus, presumably, the most impacted by the pandemic.

Statistical significance was established at the $p < 0.050$ level, applying Bonferroni's correction for multiple comparisons when appropriate.

The data analysis was generated using the Real Statistics Resource Pack software (Release 6.8) (www.real-statistics.com) for Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) and GraphPad Prism 8.4.0 (GraphPad Software, La Jolla, CA, USA).

RESULTS

In the Radiology and Neuroradiology Departments of our institution a total of 1384380 diagnostic imaging examinations were performed from 2015 to 2021 (2015-2019 $n = 1003573$; 2020 $n = 178096$; 2021 $n = 202711$). Considering the first year of pandemic, the overall annual workload was lower than in the previous five years, with an average RC of -11%. Specifically, fewer examinations were performed for all imaging modalities (RC from -19% to -25%), except for CT (RC = +11%), and all body regions (RC from -5% to -27%), apart from a slight increase in cardiovascular imaging (RC = +5%). Regarding the care setting, there was a relevant workload decrease for outpatient (RC = -31%) and pre-admission imaging (RC = -27%), while only a slight variation was observed for inpatient (+4%) and emergency imaging (-1%).

On the contrary, the total imaging workload in 2021 was almost the same as in the pre-pandemic period (RC = +1%). Among the different imaging modalities, CT was the only one to maintain a higher annual workload (RC = 18%) than in the pre-pandemic period, whereas a slight reduction was observed for the other ones (RC from -2% to -9%). Breast and cardiovascular imaging also showed a relevant workload increase, with a RC of +30% and +27%, respectively. Considering the care setting, the workload of outpatient imaging was still reduced compared the two-pre-pandemic period (RC = -18%), while it was increased for the other categories, especially for inpatient imaging (RC = +17%).

Full details of the annual workload changes between pre-pandemic and pandemic periods, overall and grouped by imaging modality, body region and care setting, are reported in Table 1. A visual representation of the monthly variation of the imaging workload in these periods is also provided in Figure 2. The same visual representations for the workload of each imaging modality, body region and care setting are provided as Supplementary Information.

Focusing on the pandemic outbreaks, during the first wave the workload for CT only slightly changed (RC = +3%), but it decreased relevantly for all other modalities (RC from -59% to -42%). A workload reduction was observed for all body regions as well, with RC ranging from -64% for breast imaging to -20% for chest imaging.

In the second pandemic wave, the number of CT examinations increased (RC = +19%), while a workload decrease,

TABLE 1. Comparison between pre-pandemic (2015-2019) and pandemic (2020-2021) workload of diagnostic imaging.

	Pre-COVID-19 (5-y Avg Mean [Min-Max])	COVID-19 (Value [Relative Change])	
		2020	2021
Overall annual workload	200715 (186724–214624)	**178096 (-11%)**	202711 (1%)
Imaging modality			
XR	106438 (96139–113078)	**86733 (-19%)**	99577 (-6%)
CT	53129 (49363–57330)	**58849 (+11%)**	**62436 (+18%)**
MRI	16806 (15135.4–24149)	**12994 (-23%)**	15273 (-9%)
US	26012 (22804–30519)	**19520 (-25%)**	25425 (-2%)
Body region			
Chest	68157 (57722–73312)	64078 (-6%)	66042 (-3%)
Abdomen	38140 (35400–41906)	**30777 (-19%)**	35711 (-6%)
Brain/Spine	33697 (30859–36272)	32128 (-5%)	35898 (+7%)
Musculoskeletal	32023 (29452–34468)	**26486 (-17%)**	33172 (+4%)
Breast	8447 (7312–10152)	**7086 (-16%)**	**10993 (+30%)**
Head/Neck	11616 (10615–12567)	**8494 (-27%)**	**9949 (-14%)**
Cardiovascular	8635 (7414–10215)	9047 (+5%)	**10946 (+27%)**
Care setting			
Inpatient	60129 (48785–69968)	62310 (+4%)	**70588 (+17%)**
Outpatient	72974 (66025–78857)	**50455 (-31%)**	**59719 (-18%)**
Emergency	62089 (57804–67007)	61291 (-1%)	66693 (+7%)
Pre-admission	5523 (5021–5933)	**4040 (-27%)**	5710 (+3%)
Chest Imaging			
Chest XR	54465 (44339–59199)	46703 (-14%)	50043 (-8%)
Chest CT	13628 (12571–14631)	**17326 (+27%)**	**15943 (+17%)**

Workload is reported as overall annual number of examinations and according to modality, body region and type of care setting. Specific workload for chest radiography and chest CT was considered as well. Relative change was calculated taking the pre-pandemic 5-year averaged (5-y avg) workload as reference. Bold values indicate when for a certain category the workload in the pandemic period was below the minimum or above the maximum value of workload in the pre-pandemic period.

CT, computed tomography; MRI, magnetic resonance imaging; US, ultrasound; XR, radiography.

albeit to a lesser extent, was still observed for all other modalities (RC from -26% to -9%). Workload by body region was also reduced (most affected: head/neck, RC = -30%; least affected: brain/spine, RC = -4%), except for breast (RC = +6%) and cardiovascular imaging (RC = +16%).

In the third pandemic wave, the workload reduction was less impactful (RC from -14% to -1%), with the increase in CT imaging remaining stable (RC = +19%). Considering examinations by body region, the results were more heterogeneous, with an increased workload for some regions (breast, RC = +29%; cardiovascular; RC = +21; brain/spine, RC = +5%) and reduced for the other ones (head/neck, RC = -18%; chest and abdomen, RC = -9%; musculoskeletal, -4%).

Finally, during the fourth pandemic wave, the workload for the different imaging modalities was almost the same as in the pre-pandemic period (RC from +2% to +5%), apart from CT workload, which remained substantially increased (RC = +17%). Regarding body regions, the workload for head/neck and abdominal imaging was still slightly reduced (RC = -8% and RC = -4%, respectively), while it was increased for the other body regions, especially for breast (RC = +34%) and cardiovascular imaging (RC = +33%).

Considering the care setting, in the first wave the workload of all categories was reduced, especially outpatient (RC = -86%) and pre-admission imaging (RC = -59%). In subsequent waves, the workload for outpatient imaging remained decreased, with a RC ranging from -28% to -12%. Instead, inpatient and emergency workload showed a gradual increase, with a RC from +3% to +20% and from -6% to +12%, respectively. Notably, the workload of pre-admission imaging was relevantly reduced both in the second (RC = -28%) and third wave (RC = -36%), but a relevant increment was observed in the fourth wave (RC = +41%).

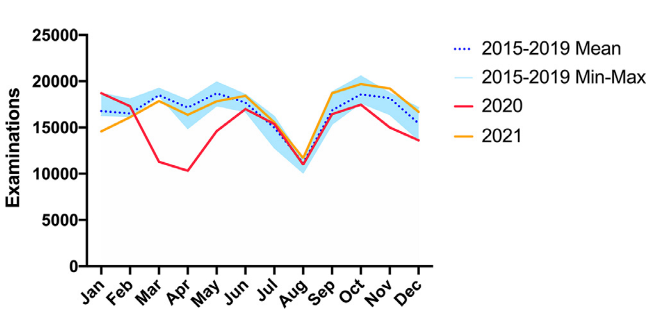

Figure 2. Monthly variation of total imaging workload in the pre-pandemic (2015-2019) and pandemic (2020 and 2021) periods. For the pre-pandemic period, mean, minimum and maximum over the 5 years are reported. (Color version of figure is available online.)

A summary of workload variation by imaging modality, body region and care setting during the different pandemic waves was provided in Figure 3 and Table 2.

The analysis of the distribution of imaging workload by care setting (Figure 4) showed that in all pandemic waves inpatient and emergency imaging were increased (from +2% to +10% in proportion to the total), while outpatient imaging was reduced (from -6% to -15% in proportion to the total). Pre-admission imaging was reduced in all pandemic waves as well (from -1 to -2%), except in the fourth one where it was slightly increased (+1%). All these differences in workload distribution were statistically significant ($p < 0.001$).

When considering the annual workload of chest XR and chest CT, the imaging modality of reference for the diagnosis and management of COVID-19 patients, the first one was decreased and the second one was increased in comparison with the pre-pandemic period (Table 1). Focusing on the pandemic waves (Figure 5), the workload of chest CT was increased in all of them (first wave, RC = +30%; second wave, RC = +55%; third wave, RC = +23%; fourth wave, RC = +14%). Instead, the workload of chest XR was reduced in the first three pandemic waves (first wave, RC = -32%; second wave, RC = -25%; third wave, RC = -17%) and only slightly changed in the fourth one (RC = +3%). Also, considering the care setting (Table 3), in all pandemic waves the workload of chest CT was increased in emergency (from +12% to +35% in proportion to the total, $p < 0.001$) and reduced in the outpatient setting (from -21% to -32% in proportion to the total, $p < 0.001$). Regarding chest XR, in all pandemic waves an increase in the inpatient (from +12% to +35% in proportion to the total, $p < 0.001$) and a decrease in the outpatient setting (from -21% to -32% in proportion to the total, $p < 0.001$) was observed. In the first and second pandemic waves, the emergency workload of chest XR was increased as well, by +2% ($p = 0.049$) and +3% ($p < 0.001$), respectively.

DISCUSSION

In this observational study, changes in diagnostic imaging workload were analyzed throughout the different pandemic waves, showing the initial plunge of the radiological examinations and the following recovery of the activities at different rates depending on the modality, body region and care setting.

The relevant decrease in workload observed in 2020, especially in the first wave of the pandemic, is not surprising. Healthcare systems were unprepared to face the exponential surge in cases of an almost unknown disease and, obviously, highly precautionary measures prevailed, both in and out of the hospital setting. As a result, between March and May 2020, imaging activities fell below the minimum of the previous five pre-pandemic years, regardless of the imaging

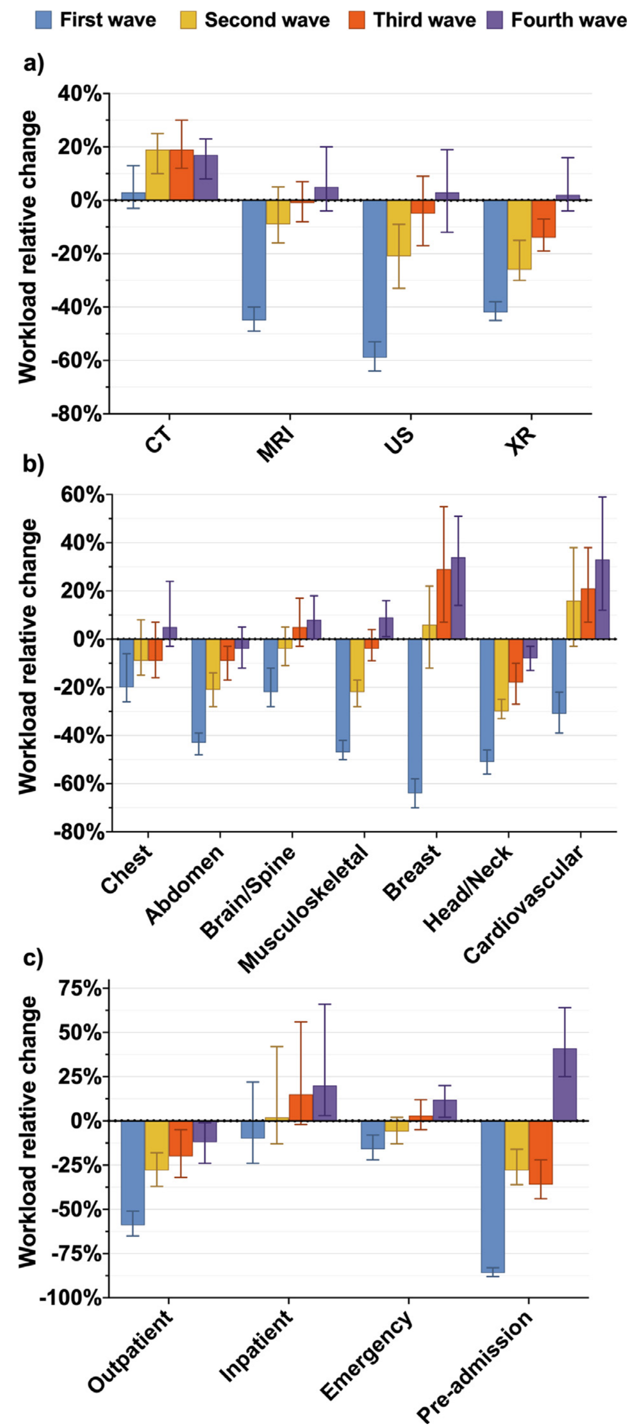

Figure 3. Changes in diagnostic imaging workload in the different COVID-19 pandemic waves compared to pre-pandemic (2015-2019) period, according to modality (a), body region (b) and care setting (c) of examinations. Rectangular boxes represent the relative change calculated taking the mean workload over the five pre-pandemic years as reference. The bars represent the relative change calculated taking the minimum and the maximum workload over the five pre-pandemic years. CT, computed tomography; MRI, magnetic resonance imaging; US, ultrasound; XR, radiography. (Color version of figure is available online.)

TABLE 2. Workload during the different pandemic waves reported as overall number of examinations and according to modality, body region and type of care setting.

	First Wave	Second Wave	Third Wave	Fourth Wave
Overall workload	**36209 (-33%)**	46087 (-12%)	52050 (-3%)	55589 (6%)
Imaging modality				
XR	**16477 (-42%)**	**20512(-26%)**	**24495(-14%)**	28080 (2%)
CT	14382 (+3%)	**16456 (+19%)**	**16606 (19%)**	**16127 (+17%)**
MRI	**2294 (-45%)**	3669 (-9%)	4095 (-1%)	4153 (+5%)
US	**3056 (-59%)**	**5450 (-21%)**	6854 (-5%)	7229 (+3%)
Body region				
Chest	**14566 (-20%)**	16217 (-9%)	16526 (-9%)	18537 (5%)
Abdomen	**5837 (-43%)**	**7823 (-21%)**	**9157 (-9%)**	9529 (-4%)
Brain/Spine	**6983 (-22%)**	8388 (-4%)	9309 (+5%)	9434 (+8%)
Musculoskeletal	**4565 (-47%)**	**6350 (-22%)**	8205 (-4%)	**8921 (+9%)**
Breast	**956 (-64%)**	2520 (+6%)	**3245 (+29%)**	**3335 (+34%)**
Head/Neck	**1572 (-51%)**	**2150 (-30%)**	**2595 (-18%)**	**2795 (-8%)**
Cardiovascular	**1730 (-31%)**	2639 (+16%)	**3013 (+21%)**	**3038 (+33%)**
Care setting				
Inpatient	13992 (-10%)	15888 (+2%)	17983 (+15%)	**18676 (+20%)**
Outpatient	**8509 (-59%)**	**14062 (-28%)**	**16588 (-20%)**	**16998 (-12%)**
Emergency	**13486 (-16%)**	15054 (-6%)	16481 (+3%)	**17800 (+12%)**
Pre-admission	**222 (-86%)**	**1083 (-28%)**	**998 (-36%)**	**2115 (+41%)**

The relative change calculated taking the pre-pandemic 5-year averaged workload as reference is reported in parentheses. Bold values indicate when for a certain category the workload in the pandemic period was below the minimum or above the maximum value of workload in the pre-pandemic period.

CT, computed tomography; MRI, magnetic resonance imaging; US, ultrasound; XR, radiography.

modality or body region of interest. The only exception was CT imaging, whose workload remained nearly unchanged compared to the pre-pandemic period and even increased throughout the other pandemic waves, reaching an increment of almost +20% and peaking at +55% when considering chest CT workload.

This can be explained by the excellent sensitivity of CT imaging for early pulmonary changes, which was crucial in a setting with limited capability of COVID-19 testing and long turnaround times, like in the first wave when only PCR tests were available (24). In the following phases, despite rapid antigenic tests being at disposal, CT scan kept a central role in diagnosing COVID-19 patients, for instance, in case of mismatch between test results and clinical findings. Also, in the third wave and, above all, in the fourth one, a growing part of the population was vaccinated, hence it was more common to deal with patients who tested positive for

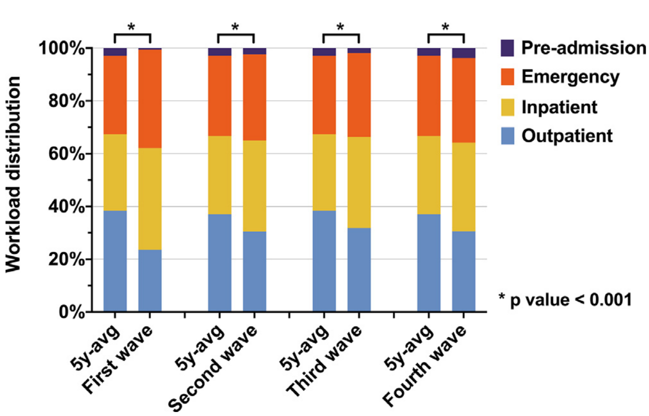

Figure 4. Visual analysis of the distribution of imaging workload by care setting comparing the different pandemic waves with the corresponding 5-year averaged (5-y avg) pre-pandemic periods (2015-2019). Percentages are calculated in proportion to the total examinations. (Color version of figure is available online.)

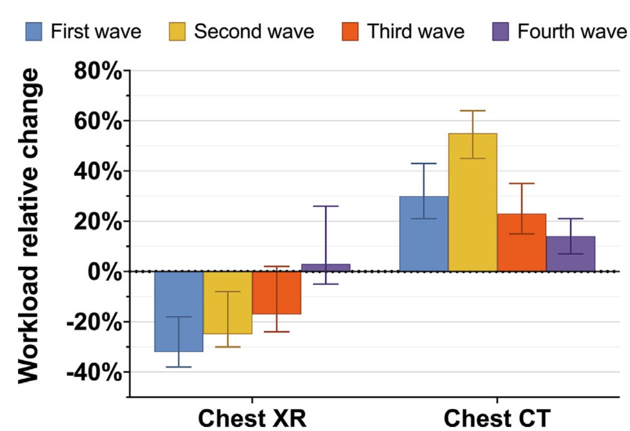

Figure 5. Workload changes in chest radiography (XR) and chest CT examinations comparing the different COVID-19 pandemic waves with the pre-pandemic (2015-2019) period. Rectangular boxes represent the relative change calculated taking the mean workload over the five pre-pandemic years as reference. The bars represent the relative change calculated taking the minimum and the maximum workload over the five pre-pandemic years. (Color version of figure is available online.)

TABLE 3. Analysis of the distribution of the workload for chest radiography (XR) and chest computed tomography (CT) comparing the different pandemic waves with the corresponding 5-year (2015-2019) averaged pre-pandemic periods.

	Outpatient		Inpatient		Emergency		Pre-Admission	
Chest XR								
Pre-pandemic	3663 (25%)	$p < 0.001$	5027 (35%)	$p < 0.001$	4419 (30%)	$p = 0.049$	1400 (10%)	$p < 0.001$
First wave	2028 (21%)		4474 (46%)		3139 (32%)		176 (2%)	
Pre-pandemic	3442 (24%)	$p < 0.001$	4857 (34%)	$p < 0.001$	4504 (32%)	$p < 0.001$	1362 (10%)	$p > 0.999$
Second wave	1926 (18%)		4636 (43%)		3099 (29%)		1027 (10%)	
Pre-pandemic	3663 (25%)	$p < 0.001$	5027 (35%)	$p < 0.001$	4419 (30%)	$p > 0.999$	1400 (10%)	$p < 0.001$
Third wave	2146 (18%)		5320 (44%)		3634 (30%)		931 (8%)	
Pre-pandemic	3442 (24%)	$p < 0.001$	4857 (34%)	$p < 0.001$	4504 (32%)	$p = 0.066$	1362 (10%)	$p < 0.001$
Fourth wave	2276 (16%)		5452 (38%)		4813 (33%)		1990 (14%)	
Chest CT								
Pre-pandemic	1861 (52%)	$p < 0.001$	1382 (39%)	$p = 0.059$	315 (9%)	$p < 0.001$	27 (1%)	$p = 0.060$
First wave	928 (20%)		1705 (36%)		2093 (44%)		17 (0.4%)	
Pre-pandemic	1749 (50%)	$p < 0.001$	1449 (41%)	$p < 0.001$	303 (9%)	$p < 0.001$	30 (1%)	$p = 0.009$
Second wave	1239 (22%)		1984 (36%)		2273 (41%)		20 (0.4%)	
Pre-pandemic	1861 (52%)	$p < 0.001$	1382 (39%)	$p = 0.178$	315 (9%)	$p < 0.001$	27 (1%)	$p = 0.219$
Third wave	1339 (30%)		1826 (41%)		1296 (29%)		19 (0.4%)	
Pre-pandemic	1749 (50%)	$p < 0.001$	1449 (41%)	$p < 0.001$	303 (9%)	$p < 0.001$	30 (1%)	$p > 0.999$
Fourth wave	1158 (29%)		1972 (49%)		827 (21%)		37 (1%)	

SARS-Coronavirus-2 but without clinically significant lung involvement (25). In this situation, CT scan became valuable to determine whether the patient really had interstitial pneumonia or was symptomatic for other causes unrelated to the infection. CT imaging was also largely used to stratify patients based on the extent of the pulmonary involvement and the presence of complications, such as superinfection or pulmonary thromboembolism (26,27). In a setting of overcrowding in the ED and shortage of intensive care beds, mechanical ventilation devices and oxygen, it was essential to discriminate between patients needing hospital admission, or at least close monitoring in a protected medical environment, and patients that could be discharged for home follow-up.

It is worth mentioning that CT imaging was recommended for COVID-19 patients in many clinical scenarios except for resource-constrained settings (24). However, other studies analyzing the workload variation by imaging modality mostly reported a reduction in CT volume during the first wave (28,29). Indeed, the increase in CT workload in our institution was possible thanks to the availability of multiple scanners. This allowed to organize dedicated imaging sessions for COVID-19 patients admitted in the ED or already hospitalized, while some scanners remained COVID-free to ensure safe examinations, especially for surgical and oncological patients. Another factor influencing the increased CT workload, especially in the second half of 2021, was the more extensive use of split-bolus CT for minor trauma patients (30) to reduce observational periods and address the need for rapid discharge from the overburdened ED. As opposed to CT imaging, XR workload was reduced in all but the last pandemic wave, including chest XR. It is reasonable to attribute the drop in pre-admission and outpatient examinations to the deferring of nonurgent services and the suspension of elective surgical procedures. However, emergency and inpatient XR were affected as well, despite the relative workload increase due to COVID-19 patients. In this case, the adoption of strict safety protocols and a sub-optimal layout of XR rooms to ensure COVID-free pathways inside our Radiology Department decreased the efficiency of this imaging modality. XR workload was maintained at nearly the same level as the pre-pandemic period only in the fourth wave, probably because of the high vaccination coverage and, consequently, the looser restrictions imposed.

MRI and US workloads were restored more rapidly, already almost in the third wave, when the vaccination coverage was still low. This was probably the result of progressively looser restrictions and the willingness of patients to make up for delayed elective examinations, but it also reflected the successful implementation of adequate organizational measures (e.g., dedicated time slots for COVID-19 inpatients or optimized cleaning protocols between outpatients). On the other hand, head/neck imaging was the only body region category whose workload remained below the minimum of the pre-pandemic period for the entire pandemic, which may be surprising since it does not require specific precautions compared to other examinations. Indeed, this may be imputed to the fact that our institution is not a hub for head/neck disease care; so, regardless of the measures taken during the pandemic, these patients were more likely referred to other dedicated centers.

The trend of breast imaging is even more intriguing. During the first wave, the workload for this body region was reduced by far the most, falling below -60%. As observed by Shi et al. (16), breast imaging was one of the most impacted categories during the pandemic because of the main component of outpatient volume. However, in the second wave, the breast imaging workload was the only one to increase along with cardiovascular imaging, maintaining in the subsequent waves an increase of +30% compared to the pre-pandemic average. This prominent build-up in breast imaging workload can be likely attributed to the less rigid restrictions, the lower level of patient concern and the more efficient organization of the hospital. In particular, it expressed the effort to preserve the provision of breast imaging services and, at the same time, to make up for missed examinations in the previous pandemic waves, especially those related to breast cancer screening according to the recommendations from the Italian College of Breast Radiologists (31). This was crucial because reduced imaging volumes represent delayed medical care, with a negative impact on patient prognosis (32). The same effort to recover the surgical procedures postponed in the previous pandemic outbreaks resulted in the peak of pre-admission imaging in the fourth wave.

The abovementioned reasons applied also to cardiovascular examinations, which showed a marked workload decrease in the first pandemic wave (-31%) but rapid recovery in the following pandemic outbreaks, even exceeding the number of examinations in the pre-pandemic period by more than +30%. However, two additional factors contributed to raising the cardiovascular imaging volume in our institution. On the one hand, a new, higher-performance CT scanner was installed between the first and the second pandemic waves, allowing more cardiovascular examinations to be acquired. On the other hand, the indications of cardiac CT for the diagnosis of coronary artery disease are steadily widening, as is the number of patients who are offered endovascular treatment and, therefore, require a CT angiography (33,34).

In general, as regards the first pandemic wave, the results of our analysis are comparable to early studies that reported a relevant reduction in diagnostic imaging workload (17,19,29), highlighting the role of complete national lockdown and the lack of adequate healthcare resources to cope with the abrupt COVID-19 outbreak. The impact of the subsequent pandemic waves was gradually less pronounced because they were preceded by a renewal of the growth of COVID-19 cases in the community, which allowed to prepare and implement more efficient COVID-19 protocols. However, hospitals were still overburdened due to the wider spread of the coronavirus in the population, so the need to ensure the safety of healthcare workers and patients and the shift of resources to COVID-19 patient care hampered the resumption of the pre-pandemic imaging workload. Our study showed that an effective organization of the hospital resources, ensuring availability of healthcare services, was reached almost only in the last wave, almost 18 months after the pandemic beginning, thanks to the synergetic contribution of high vaccination coverage that drastically reduced the proportion of patients actually needing emergency care and/or hospitalization.

The retrospective design in a single tertiary referral hospital was the main limitation of this study since the results of our analysis may vary in other institutions with different local practice patterns and resource availability. Also, we could have used different periods to define the pandemic waves, although we attempted to limit subjectivity by basing our choice on the trend of epidemiological data and the tightening/loosening of restrictions. Moreover, the analysis of the workload variations during the "inter-wave" periods was not considered (albeit a visual representation is provided as Supplementary Material) to keep the focus on the factors that conditioned the workload variations during the different COVID-19 outbreaks. Even if the four pandemics likely gave an effective approximation of the global trend of imaging workload variation, in the future it would be desirable to integrate this information. Collecting and pooling data from various national and international centers is also warranted to understand how different expertise and hospital catchment area have affected the workload and the organization of diagnostic imaging activities.

In conclusion, our analysis confirmed the prolonged, high impact of COVID-19 on the radiological workload, but also offers a broad view of the temporal evolution and modalities of response to the succession of different pandemic waves, progressively resuming to normal − and in some cases even greater − operating capacity. Understanding these dynamics is the key to improving the responsiveness of healthcare institutions and planning the reorganization of imaging services to face extreme contingency situations.

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AUTHOR CONTRIBUTIONS

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All Authors read and approved the final manuscript.

ETHICS APPROVAL AND INFORMED CONSENT

This study was performed in line with the principles of the Declaration of Helsinki. The study was approved by the Local Ethics Committee (decision number: 188-22042020). Since data were collected retrospectively in aggregated form without including patient images, informed consent was waived.

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SUPPLEMENTARY MATERIALS

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.acra.2022.06.002.