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Editorial Board Member of *World Journal of Radiology*, Alexander B Konovalov, PhD, Associate Professor, Leading Scientist, Russian Federal Nuclear Center - Zababakhin Institute of Applied Physics, Snezhinsk 456770, Russia. a_konov@mail.vega-int.ru

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Retrospective Study

Imaging volumes during COVID-19: A Victorian health service experience

Jo-Anne Pinson, My Linh Diep, Vinay Krishnan, Caroline Aird, Cassie Cooper, Christopher Leong, Jeff Chen, Nicholas Ardley, Eldho Paul, Mohamed Khaldoun Badawy

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Jo-Anne Pinson, My Linh Diep, Vinay Krishnan, Caroline Aird, Cassie Cooper, Christopher Leong, Jeff Chen, Nicholas Ardley, Mohamed Khaldoun Badawy, Monash Health Imaging, Monash Health, Clayton, Victoria 3168, Australia

Jo-Anne Pinson, Department of Medical Imaging, Peninsula Health, Melbourne, Victoria 3099, Australia

Jo-Anne Pinson, Mohamed Khaldoun Badawy, Department of Medical Imaging and Radiation Sciences, School of Allied Health Care, Faculty of Medicine, Nursing and Health Sciences, Monash University, Clayton, Victoria 3800, Australia

Eldho Paul, Department of Epidemiology and Preventive Medicine, School of Public Health and Preventive Medicine, Monash University, Melbourne, Victoria 3800, Australia

Corresponding author: Mohamed Khaldoun Badawy, BSc, MSc, PhD, Senior Lecturer, Senior Scientist, Monash Health Imaging, Monash Health, 246 Clayton Road, Clayton, Victoria 3168, Australia. mohamed.badawy@monashhealth.org

Abstract

BACKGROUND

The World Health Organisation declared the coronavirus disease 2019 (COVID-19) a pandemic on March 11, 2020. While globally, the relative caseload has been high, Australia's has been relatively low. During the pandemic, radiology services have seen significant changes in workflow across modalities and a reduction in imaging volumes.

AIM

To investigate differences in modality imaging volumes during the COVID-19 pandemic across a large Victorian public health network.

METHODS

A retrospective analysis from January 2019 to December 2020 compared imaging volumes across two periods corresponding to the pandemic's first and second waves. Weekly volumes across patient class, modality and mobile imaging were summed for periods: wave 1 (weeks 11 to 16 for 2019; weeks 63 to 68 for 2020) and wave 2 (weeks 28 to 43 for 2019; weeks 80 to 95 for 2020). Microsoft Power Business Intelligence linked to the radiology information system was used to mine

all completed examinations.

RESULTS

Summed weekly data during the pandemic's first wave showed the greatest decrease of 29.8% in adult outpatient imaging volumes and 46.3% in paediatric emergency department imaging volumes. Adult nuclear medicine demonstrated the greatest decrease of 37.1% for the same period. Paediatric nuclear medicine showed the greatest decrease of 47.8%, with angiography increasing by 50%. The pandemic's second wave demonstrated the greatest decrease of 23.5% in adult outpatient imaging volumes, with an increase of 18.2% in inpatient imaging volumes. The greatest decrease was 28.5% in paediatric emergency department imaging volumes. Nuclear medicine showed the greatest decrease of 37.1% for the same period. Paediatric nuclear medicine showed the greatest decrease of 36.7%. Mobile imaging utilisation increased between 57.8% and 135.1% during the first and second waves. A strong correlation was observed between mobile and non-mobile imaging in the emergency setting (Spearman's correlation coefficient = -0.743, $P = 0.000$). No correlation was observed in the inpatient setting (Spearman's correlation coefficient = -0.059, $P = 0.554$).

CONCLUSION

Nuclear medicine was most impacted, while computed tomography and angiography were the least affected by the pandemic. The impact was less during the pandemic's second wave. Mobile imaging shows continuous growth during both waves.

Key Words: COVID-19; Pandemic; Radiology; Imaging volume; Modality; Mobile imaging

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Core Tip: Analysis of weekly imaging modality volumes provides an overview of changes in service demand over time. We describe the changes in imaging modality and mobile imaging volumes during Victoria's first and second waves of the coronavirus disease 2019 pandemic.

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INTRODUCTION

The World Health Organisation declared the coronavirus disease 2019 (COVID-19) a pandemic on March 11, 2020[1]. Healthcare facilities implemented strict infection control, social distancing protocols, and other measures in the interest of public health and safety[2]. In preparation for the surge in hospitalisations across the globe, overall elective surgical services decreased by approximately 72%[3]. In comparison, in Australia, this fell by about 69%. Others utilised computational modelling to help predict the health services saturation point for ICU beds and ventilators[4]. While globally, the relative caseload has been high, Australia's has been relatively low. In this context, during 2020, Victoria has experienced most of Australia's cases, with the new daily caseloads shown in Figure 1.

Due to the overwhelming prevalence of COVID-19 in various countries, for example, Italy, some radiology departments were dedicated to imaging COVID-19 patients only[5]. Radiology services have also seen significant changes in workflow across modalities and a reduction in imaging volumes[6-8]. For example, departments were re-configured to separate COVID-19 patients from non-infected patients, segregation of staff to reduce infection transmission, increased demand for PPE, radiologists reporting from home, and expansion of video conferencing use[5,9]. For patients presenting to the emergency department, general radiography was primarily used due to its accessibility, availability and low radiation levels. The chest X-ray was an ideal first choice for patients with typical symptoms of COVID-19, such as shortness of breath on exertion, persistent cough and chest pain [8]. To minimise the transmission risk of suspected COVID-19 (sCOVID) patients in hospital, mobile imaging became particularly important to manage workflow[10,11]. Imaging in the ward wearing PPE could reduce staff exposure, with effective cleaning of mobile units possible between imaging patients, without compromising patient care.

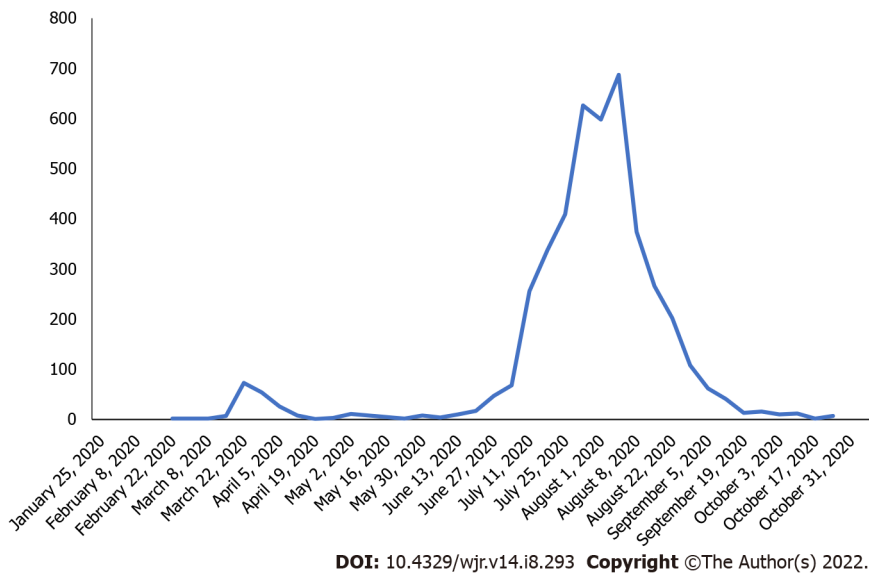


Figure 1 Victorian new the coronavirus disease 2019 case numbers by date from January 2020–November 2020.

While it has been reported, there was a decrease in patients presenting with stroke to our institution during the pandemic[7]. To our knowledge, little is known about the severity of impact on radiology volumes in Australia. While overall Australian imaging volumes were analysed through Medicare, no institutional experience has been presented[12].

Objectives

This study investigates the imaging volume changes during the pandemic across the network at a large Victorian public health service provider. A secondary aim was to study changes in mobile imaging utilisation and whether that impacted the use of fixed (non-mobile) X-ray imaging systems. This data will help inform radiology practices for service adaptation with subsequent pandemic phases or other “once in a lifetime” events.

MATERIALS AND METHODS

This health network has 98 imaging systems across eight imaging modalities analysed according to Table 1.

Study setting

Our network provided over three million episodes of care from 2019 to 2020. Three of our five hospitals provide accident and emergency services, and one is a geriatric centre, and the other is an oncology centre that did not service COVID-19-positive patients (‘clean site’). Data from the geriatric and oncology centre were excluded due to heterogeneity in these sites. Significant federal, state and local health policy and guideline changes were implemented and updated during the pandemic that impacted the imaging pathway, including: patients with typical respiratory symptoms (fever, chest tightness, dyspnoea, cough) were classified as sCOVID-19 (suspected COVID-19); recommendation for all eligible sCOVID-19 patients to have computed tomography (CT) pulmonary angiography (CTPA) instead of V/Q scans[13]; rescheduling of non-urgent cases as discussed with referring clinicians; use of mobile X-ray to reduce infection transmission; social distancing guidelines restricting patient waiting room numbers and minimum area of 4 m² per person in shared spaces.

Data collection

Microsoft Power Business Intelligence, linked to the radiology information system, was used to mine all completed examinations between January 1, 2019 and December 31, 2020 across three sites. Imaging modality was defined as the device or technology used in medical imaging (general X-ray, mammography, nuclear medicine, CT, magnetic resonance imaging (MRI), fluoroscopy, angiography, ultrasound, with mobile X-ray being a subset of X-ray). Fixed or non-mobile imaging was an X-ray system permanently secured in an X-ray room. Mobile imaging was defined as using a portable X-ray imaging system capable of moving to different locations. Patient classes were defined by location (inpatient (IP), outpatient (OP) or emergency department (ED)). Adult patients were ≥ 16 years, while paediatric patients were aged < 16 years. Examinations were filtered by modality and patient class.

Table 1 List of equipment number across all modalities

Modality	MRI	NM	BMD	CT	X-ray	Fluoro	US	Angio
Equip No.	5	6	2	7	26	4	45	3

MRI: Magnetic resonance imaging; NM: Nanometer; BMD: Bone mineral densitometry; CT: Computed tomography; Fluoro: Fluoroscopy; US: Ultrasound; Angio: Angiography.

March 2020 and April 2020 [week 63 (March 11 to March 17) to week 68 (April 15 to April 21)] corresponded to Victoria's first wave of the pandemic; July 2020 to October 2020 [week 80 (July 9 to July 14) to week 95 (October 21 to October 26)] corresponded to the second wave of the pandemic. **Figure 2** provides the timeline of the first and second waves for considering the impact on departmental caseloads. The outcome measure was total weekly completed imaging case numbers from Wednesday to Tuesday commencing Wednesday January 2 to Tuesday January 8, 2019 (week 1) for direct day matched weekly comparisons between 2019 and 2020, allowing for any periodic variability observed. Weekly modality data were summed to reflect the first and second waves of the pandemic.

Statistical analysis

Weekly volumes across patient class, modality and mobile imaging were summed for defined periods: wave 1 (weeks 11 to 16 for 2019; weeks 63 to 68 for 2020) and wave 2 (weeks 28 to 43 for 2019; weeks 80 to 95 for 2020). This was to evaluate the impact of COVID-19 on patient class, modality and mobile imaging case volumes during each COVID-19 wave. For analysis of mean weekly case numbers, pre-COVID data were defined as weeks 1 to 60 (*i.e.*, January 2, 2019 to February 29, 2020), while COVID-19 data were defined as the mean of weeks 61 to 104 (*i.e.*, March 1, 2020 to December 31, 2020). Independent sample *t*-tests were performed comparing the mean weekly imaging case volumes in the years 2020 and 2019 for each imaging modality type stratified by patient service locations for the pre-COVID-19 and post-COVID-19 periods with results presented as means and 95% confidence intervals (95%CI). The relationship between mobile and non-mobile imaging volumes was assessed using Spearman rank correlation. Statistical significance was considered for *p* values < 0.05. All analyses were performed using SAS version 9.4 (SAS Institute, Cary, NC, United States). Dr Eldho Paul reviewed the statistical methods of this study from Monash University.

This study was approved by the Monash Health Human Research Ethics Committee.

RESULTS

Adults

Total volume (all modalities): During the pandemic's first wave in Victoria, total adult imaging volume across all modalities declined by 20.7% between March 11 and April 21, 2020 (weeks 63 to 68) compared to the same time in 2019 (March 13 and April 23, 2019, weeks 11 to 16). During the pandemic's second wave, adult imaging volume across all modalities declined by 6.6% between July 8, and October 27, 2020 (weeks 80 to 95) compared to the same time in 2019 (July 10, and October 29, 2019, weeks 28 to 43).

Volume by patient class

Table 2 shows the summed weekly imaging volumes for the defined periods and the percentage of adult image volume change across all included modalities by patient class for weeks 11 to 16 (March 13 and April 23) and 28 to 43 (July 10 and October 29) in 2019 and weeks 63 to 68 (March 11 and April 21) and 80 to 95 (July 8 and 2October 27) in 2020.

Volume by modality: During the pandemic's first wave between March 11 and April 21, 2020 (weeks 63 to 68), adult angiography, bone mineral densitometry, computed tomography, fluoroscopy, general radiography, magnetic resonance imaging, mammography, nuclear medicine and ultrasound imaging volumes declined between 10.3% and 37.1% when compared to the same time in 2019 (March 13 and April 23, 2019, weeks 11 to 16) shown in **Table 3**.

During the pandemic's second wave between July 8 and October 27, 2020 (weeks 80 to 95), adult angiography, bone mineral densitometry, fluoroscopy, general radiography, magnetic resonance imaging, mammography, nuclear medicine and ultrasound services declined between 1.6% and 31.6%, while computed tomography increased by 1.7% when compared to the same time in 2019 (July 10 and October 29, 2019, weeks 28 to 43) shown in **Table 4**.

Figure 3 highlights the weekly adult modality imaging volumes.

Comparison of the adult mean weekly 2019 (pre-COVID-19, January 1, 2019 to February 29, 2020, weeks 1 to 61) with 2020 (March 1 to December 31, 2020 weeks 61 to 104) imaging volumes by modality, categorised by inpatient, outpatient and emergency services (**Table 5**) shows statistically significant

Table 2 Summed imaging volumes and percentage change in adult imaging volume across patient class in waves 1 and 2

Wave 1	2020 (weeks 63-68)	2019 (weeks 11-16)	% change	Wave 2	2020 (weeks 80-95)	2019 (weeks 28-43)	% change
ED	9521	12783	-25.5	ED	29454	32262	-8.7
IP	9210	9395	-2.0	IP	31424	26576	18.2
OP	8874	12636	-29.8	OP	26967	35236	-23.5
Overall	27605	34814	-20.7	Overall	87845	94074	-6.6

ED: Emergency department; IP: Inpatient; OP: Outpatient.

Table 3 Summed imaging volumes and percentage change in adult imaging volumes across modalities in wave 1

Wave 1	2020 (weeks 63-68)	2019 (weeks 11-16)	%
Angiography	269	300	-10.3
Bone Mineral Densitometry	185	239	-22.6
Computed Tomography	5883	6688	-12.0
Fluoroscopy	766	968	-20.9
General Radiography	11668	15311	-23.8
Magnetic Resonance Imaging	2013	2709	-25.7
Mammography	82	123	-33.3
Nuclear Medicine	394	626	-37.1
Ultrasound	6345	7850	-19.2
Total	27605	34814	-20.7

Table 4 Summed imaging volumes and percentage change in adult imaging volume across modalities in wave 2

Wave 2	2020 (weeks 80-95)	2019 (weeks 28-43)	%
Angiography	822	835	-1.6
Bone mineral densitometry	690	892	-22.6
Computed tomography	19316	18997	1.7
Fluoroscopy	2313	2550	-9.3
General radiography	36845	40592	-9.2
Magnetic resonance imaging	6685	7539	-11.3
Mammography	303	334	-9.3
Nuclear medicine	1149	1679	-31.6
Ultrasound	19722	20656	-4.5
Total	87845	94074	-6.6

declines in six imaging modalities ($P = 0.042$ to $P < 0.0001$). There were statistically significant declines in one inpatient imaging modality ($P = 0.002$) and nine outpatient imaging modalities ($P = 0.027$ to $P < 0.0001$). Statistically significant increases were observed in five inpatient modalities ($P = 0.0003$ to $P < 0.0001$). All patient classes observed overall declines across seven imaging modalities ($P = 0.027$ to $P < 0.0001$).

Mobile and non-mobile X-ray imaging: During the pandemic's first wave in Victoria, total adult mobile imaging volume increased by 57.8% between March 11 and April 21, 2020 (weeks 63 to 68) compared to the same time in 2019 (March 13 and April 23, 2019, weeks 11 to 16). During the pandemic's second wave, adult mobile imaging volume increased by 135.1% between July 8 and October 27, 2020 (weeks 80 to 95) compared to the same time in 2019 (July 10 and October 29, 2019, weeks 28 to 43). **Table 6** highlights the mobile imaging changes across inpatient and emergency patient classes during the first

Table 5 Comparison of mean adult weekly imaging volumes for 2019 and 2020 including 95%CI, by imaging modality categorised by patient setting

Adult Setting	Modality	2020			2019			P value
		Mean	Min-max	95%CI	Mean	Min-max	95%CI	
Emergency	Angiography	4.05	1-10	3.38-4.71	5.03	2-12	4.51-5.56	0.02
	Computed tomography	541.2	384-663	520-562.4	548.68	473-606	541.7-555.7	0.453
	Fluoroscopy	5.18	1-12	4.31-6.05	4.15	0-11	3.58-4.72	0.042
	Radiography	1162.64	925-1309	1133.02-1192.25	1299.03	1156-1446	1281.05-1317.02	< 0.0001
	Magnetic resonance imaging	12.11	3-27	10.35-13.87	18.55	9-30	17.09-20.01	< 0.0001
	Nuclear Medicine	3.27	0-8	2.66-3.88	7.55	0-21	6.43-8.67	< 0.0001
	Ultrasound	122.98	85-157	117.52-128.43	172.13	116-255	163.72-180.55	< 0.0001
	Mammography	0	0-0	0-0	0.02	-0.02-0.05	0-0.1	0.394
Inpatient	Angiography	38.8	23-53	36.25-41.34	29.48	17-43	27.94-31.02	< 0.0001
	Computed tomography	408.05	277-498	392.38-423.71	298.87	210-416	285.57-312.16	< 0.0001
	Fluoroscopy	125.98	82-162	120.33-131.63	129.25	80-155	125.39-133.11	0.325
	Radiography	855.64	557-1015	824.02-887.25	794.77	685-968	779.87-809.67	0.0003
	Magnetic resonance imaging	123.09	74-158	117.84-128.34	100.65	67-132	97.32-103.98	< 0.0001
	Nuclear Medicine	21.64	8-37	19.76-23.52	20.92	12-35	19.68-22.15	0.507
	Ultrasound	325.82	215-395	314.29-337.35	264.22	192- 323	256.97-271.46	< 0.0001
	Mammography	0.7	0-7	0.3-1.1	1.87	0-10	1.3-2.43	0.002
Outpatient	Bone mineral densitometry	1.41	0-5	0.97-1.85	1.6	0-5	1.27-1.93	0.479
	Angiography	9.0	2-26	7.47-10.53	17.08	5-30	15.86-18.31	< 0.0001
	Computed tomography	249.86	107-333	234.48-265.25	313.7	139-367	302.61-324.79	< 0.0001
	Fluoroscopy	17.61	6-37	15.2-20.03	24.78	5-43	22.97-26.59	< 0.0001
	Radiography	268.02	120-473	246.82-289.23	427.12	147-507	410.57-443.66	< 0.0001
	Magnetic resonance imaging	268.09	98-414	249.76-286.43	347.6	108-401	335.36- 359.84	< 0.0001
	Nuclear medicine	50.84	19-88	46.88-54.8	71.72	31-112	68.14-75.3	< 0.0001
	Ultrasound	768.48	492-943	741.33-795.62	855.27	554-931	836.21-874.32	< 0.0001
All classes	Mammography	15.82	2-24	14.2-17.44	17.75	8-23	16.87-18.63	0.027
	Bone mineral densitometry	36.77	4-72	301.13-42.42	50.9	0-72	47.57-54.23	< 0.0001
	Angiography	51.84	30-70	48.58-55.11	51.6	30-63	49.76-53.44	0.892
	Computed tomography	1199.11	768-1458	1154.65-1243.58	1161.25	962-1339	1141.96-1180.54	0.090
	Fluoroscopy	148.77	96-205	141.2-145.35	158.18	92-184	153.59-162.78	0.027
	Radiography	2286.3	1602-2603	2214.97-2357.62	2520.92	2310-2718	2498.03-2543.80	< 0.0001
	Magnetic resonance imaging	403.30	175-556	380.71-425.88	466.8	200-526	452.6-481.0	< 0.0001
	Nuclear medicine	75.75	29-128	70.65-80.85	100.18	46-134	96.21-104.15	< 0.0001
	Ultrasound	1217.27	808-1491	1178.47-1256.08	1291.62	918-1429	1268.35-1314.88	.001
	Mammography	16.52	2-24	14.87-18.17	19.63	10-30	18.61-20.66	0.001
	Bone mineral densitometry	38.18	5-74	32.33-44.03	52.5	0-72	49.13-55.87	< 0.0001
	Total	5437.05	3520-6441	5250.9-5623.8	5822.68	4645-6175	5750.97- 5894.4	< 0.0001

and second waves.

Comparison of the adult mean weekly 2019 (pre-COVID-19, January 2, 2019 to February 29, 2020, weeks 1 to 61) with 2020 (March 1 to December 31, 2020, weeks 61 to 104) mobile and non-mobile X-ray

Table 6 Summed imaging volumes and percentage change in adult mobile imaging volume across patient class in waves 1 and 2

Wave 1	2020 (weeks 63-68)	2019 (weeks 11-16)	% change	Wave 2	2020 (weeks 80-95)	2019 (weeks 28-43)	% change
ED	1952	372	424.7	ED	7526	1037	625.7
IP	2008	2138	-6.1	IP	8654	5845	48.1
Overall	3960	2510	57.8	Overall	16180	6882	135.1

ED: Emergency department; IP: Inpatient.

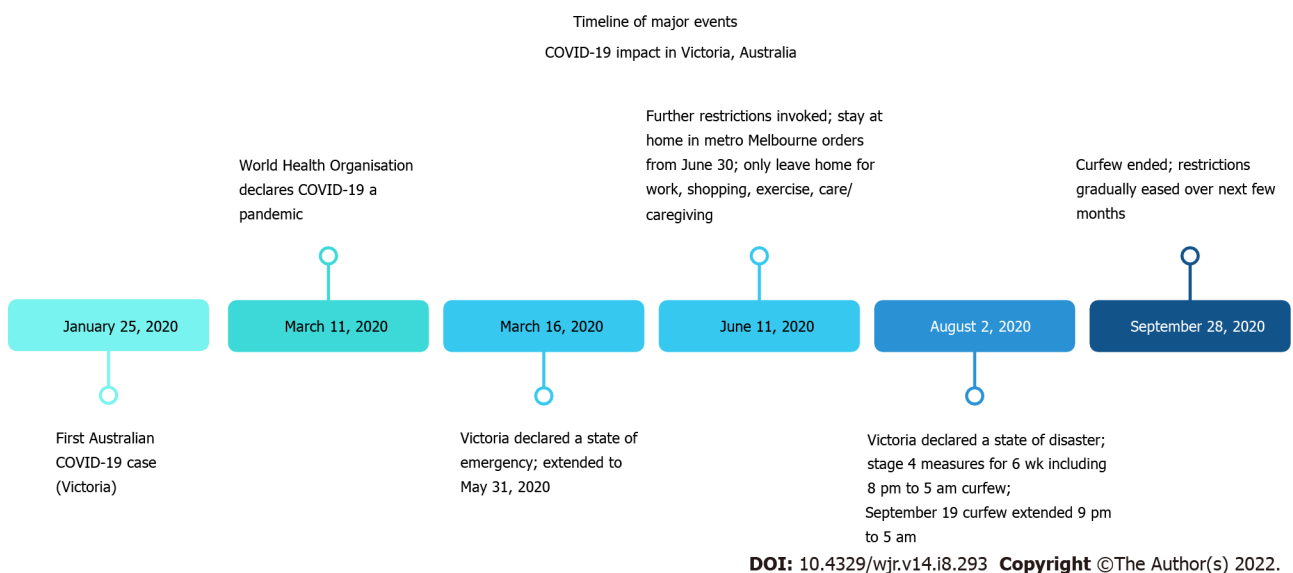


Figure 2 Timeline of significant events in Victoria, Australia during the first and second waves of the coronavirus disease 2019 pandemic. COVID-19: The coronavirus disease 2019.

imaging volumes, categorised by inpatient and emergency services (Table 7) shows statistically significant changes across all mobile and non-mobile imaging ($P = 0.001$ to < 0.0001). A strong correlation was observed between mobile and non-mobile imaging in the emergency setting (Spearman's correlation coefficient = -0.743 , $P = 0.000$). No correlation was observed in the inpatient setting (Spearman's correlation coefficient = -0.059 , $P = 0.554$). Figure 4 shows the weekly adult X-ray mobile and non-mobile imaging volumes.

Paediatrics

Total volume (all modalities): Total paediatric imaging volume across all modalities declined by 28.6% between March 11 and April 21, 2020 (weeks 63 to 68) compared to the same time in 2019 (March 13 and April 23, 2019, weeks 11 to 16). During the pandemic's second wave, paediatric imaging volume across all modalities declined by 6.6% between July 8 and October 27, 2020 (weeks 80 to 95) compared to the same time in 2019 (July 10 and October 29, 2019, weeks 28 to 43).

Volume by patient class: Table 8 shows the percentage of paediatric image volume change across all included modalities by patient class for weeks 11 to 16 and 28 to 43 in 2019 and weeks 63 to 68 and 80 to 95 in 2020.

During the pandemic's first wave between March 11 and April 21, 2020 (weeks 63-68), paediatric IP, OP and ED services declined by between 3.7% and 46.3% when compared to the same time in 2019 (March 13 and April 23 2019, weeks 11 to 16).

During the pandemic's second wave between July 8 and October 27, 2020 (weeks 80 to 95), paediatric IP, OP and ED services declined by between 16.1% and 28.5% when compared to the same time in 2019 (July 10 and October 29, 2019, weeks 28 to 43).

Volume by modality: During the pandemic's first wave between March 11 and April 21, 2020 (weeks 63 to 68), paediatric imaging modality services declined by between 18.6% and 47.8% and 18.6%, while angiography increased by 50% when compared to the same time in 2019 (March 13 and 23rd April 2019, weeks 11 to 16 shown in Table 9).

Table 7 Comparison of mean adult weekly imaging volumes for 2019 and 2020 including 95%CI, by mobile and non-mobile imaging categorised by patient setting

Adult Setting	Modality	2020			2019			P value
		Mean	Min-max	95%CI	Mean	Min-max	95%CI	
Emergency	Mobile	366.64	63- 550	330.11-403.17	63.23	45-85	60.86-65.61	< 0.0001
	Non-mobile	783.59	574-1190	739.11-828.08	1234.33	1095-1385	1216.54-1252.13	< 0.0001
Inpatient	Mobile	451.25	240-614	420.38-482.12	355.65	298-417	348.44-362.86	< 0.0001
	Non-mobile	404.00	310-514	386.64-421.36	438.93	339-564	428.10-449.77	0.001

Table 8 Summed imaging volumes and percentage change in paediatric imaging volume across patient class in waves 1 and 2

Wave 1	2020 (weeks 63-68)	2019 (weeks 11-16)	% change	Wave 2	2020 (weeks 80-95)	2019 (weeks 28-43)	% change
ED	804	1498	-46.3	ED	2780	3887	-28.5
IP	1799	2571	-30.0	IP	5818	6938	-16.1
OP	1162	1207	-3.7	OP	3041	3776	-19.5
Overall	3765	5276	-28.6	Overall	11639	14601	-20.3

ED: Emergency department; IP: Inpatient; OP: Outpatient.

Table 9 Summed imaging volumes and percentage change in paediatric imaging volume across modalities in wave 1

Wave 1	2020 (weeks 63-68)	2019 (weeks 11-16)	%
Angiography	9	6	50
Bone mineral densitometry	16	22	-27.3
Computed tomography	71	96	-26.0
Fluoroscopy	120	148	-18.9
General radiography	1896	2936	-35.4
Magnetic resonance imaging	253	340	-25.6
Nuclear medicine	12	23	-47.8
Ultrasound	1388	1705	-18.6

During the pandemic's second wave between July 8 and October 27, 2020 (weeks 80 to 95), paediatric imaging modality services declined by between 5.2% and 36.7% when compared to the same time in 2019 (July 10 and October 29, 2019, weeks 28 to 43), shown in Table 10. Figure 5 highlights the weekly paediatric modality imaging volumes.

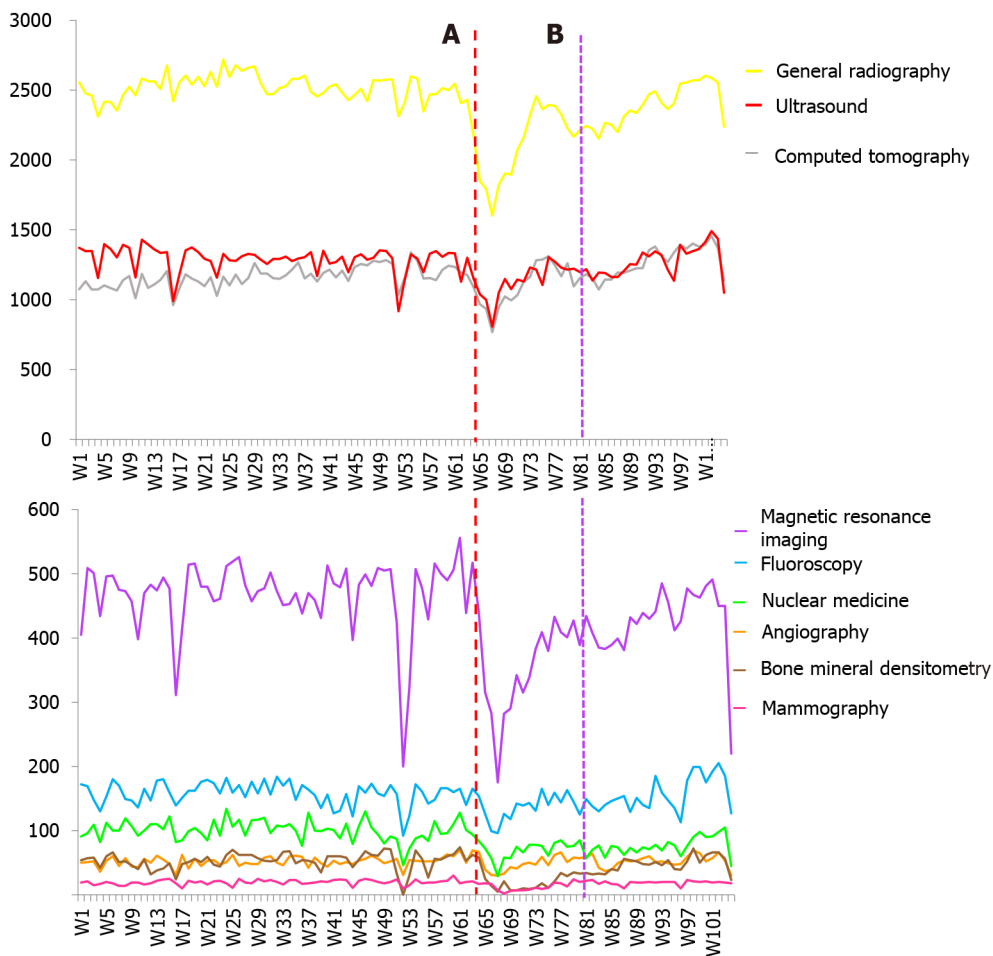
Comparison of the paediatric mean weekly 2019 (pre-COVID-19, Jan 2nd 2019 to 29th Feb 2020, weeks 1 to 61) with 2020 (March 1st to Dec 31st 2020 weeks 61 to 104) imaging volumes by modality, categorised by inpatient, outpatient and emergency services (Table 11) shows statistically significant changes in two emergency imaging modalities ($P = 0.0001$ to $P < 0.0001$), two inpatient imaging modalities ($P = 0.0003$ to $P < 0.0001$), and four outpatient imaging modalities ($P = 0.019$ to $P < 0.0001$). Overall changes across all patient classes were observed in five imaging modalities ($P = 0.037$ to $P < 0.0001$).

Mobile and non-mobile X-ray imaging: During the pandemic's first wave in Victoria, total paediatric mobile imaging volume decreased by 0.7% between March 11 and April 21, 2020 (weeks 63 to 68) compared to the same time in 2019 (March 13 and April 23 2019, weeks 11 to 16). During the pandemic's second wave, paediatric mobile imaging volume decreased by 6.7% between July 8 and October 27, 2020 (weeks 80 to 95) compared to the same time in 2019 (July 10 and October 29, 2019, weeks 28 to 43). Table 12 highlights the mobile imaging changes across inpatient and emergency patient classes during the first and second waves.

Comparison of the paediatric mean weekly 2019 (pre-COVID-19, Jan 2nd 2019 to 29th Feb 2020, weeks 1 to 61) with 2020 (March 1st to Dec 31st 2020 weeks 61 to 104) mobile and non-mobile X-ray imaging volumes, categorised by inpatient and emergency services (Table 13) shows statistically significant

Table 10 Summed imaging volumes and percentage change in paediatric imaging volume across modalities in wave 2

Wave 2	2020 (weeks 80-95)	2019 (weeks 28-43)	%
Angiography	19	23	-17.4
Bone mineral densitometry	56	68	-17.6
Computed tomography	226	241	-6.2
Fluoroscopy	314	397	-20.9
General radiography	5472	7938	-31.1
Magnetic resonance imaging	874	922	-5.2
Nuclear medicine	38	60	-36.7
Ultrasound	4640	4952	-6.3



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Figure 3 Weekly adult imaging volumes by modality from January 2019 to December 2020 (Weeks 1 to 104). A: Week 63-commencement of first wave; B: Week 80-commencement of second wave.

changes across all mobile and non-mobile imaging ($P = 0.025$ to < 0.0001). The correlation between mobile and non-mobile imaging was -0.29 ($P = 0.003$) in the emergency setting, while no correlation was observed in the inpatient setting (Spearman correlation coefficient 0.044 , $P = 0.656$). Figure 6 highlights the weekly paediatric X-ray mobile and non-mobile imaging volumes.

DISCUSSION

We found a reduction in the imaging volume between 2% and 30% across all adult patient classes and

Table 11 Comparison of mean paediatric weekly imaging volumes for 2019 and 2020 including 95%CI, by imaging modality categorised by patient setting

Paediatric Setting	Modality	2020			2019			P value
		Mean	Min-max	95%CI	Mean	Min-max	95%CI	
Emergency	Angiography	0.02	0-1	-0.02-0.07	0.02	0-1	-0.02-0.05	-0.83
	Computed tomography	4.3	0-11	3.54-5.05	5.0	0-12	4.33-5.67	0.17
	Fluoroscopy	2.27	0-6	1.68-2.86	2.53	0-7	2.08-2.99	0.48
	Radiography	160.77	75-281	144.44 -177.11	206.58	123-268	198.64-214.52	< 0.0001
	Magnetic resonance imaging	1.7	0-5	1.33-2.08	1.87	0-5	1.49-2.24	0.55
	Nuclear Medicine	0.07	0-1	-0.01-0.15	0.05	0-1	-0.01-0.11	0.70
	Ultrasound	14.41	6-25	13.16-15.65	17.67	8-26	16.59-18.74	0.0001
Inpatient	Angiography	1.18	0-4	0.83-1.53	1.17	0-6	0.85-1.48	0.95
	Computed tomography	5.66	1-14	4.92-6.4	5.66	0-11	5.0-6.27	0.96
	Fluoroscopy	17.8	7-38	15.86-19.73	19.98	7-30	18.61-21.36	0.061
	Radiography	85.84	56-120	81.74-89.94	97.97	70-143	93.99- 101.95	< 0.0001
	Magnetic resonance imaging	25.73	11-41	23.6-27.86	25.05	8-41	23.41-26.69	0.61
	Nuclear Medicine	0.55	0-3	0.28-0.81	0.98	0-5	0.72-1.25	0.025
	Ultrasound	58.36	33-76	55.51-61.21	65.33	40-84	62.9-67.77	0.0003
Outpatient	Bone mineral densitometry	0.82	0-4	0.47-1.17	1.27	0-4	1.01-1.53	0.038
	Angiography	0.05	0-1	-0.02-0.11	0.38	0-3	0.20-0.57	0.003
	Computed tomography	4.43	1-9	3.82-5.04	4.28	0-10	3.75-4.82	0.72
	Fluoroscopy	2.25	0-7	1.7-2.8	2.72	0-9	2.22-3.22	0.22
	Radiography	121.2	66-197	110.62-131.79	167.88	87-215	161.21-174.55	< 0.0001
	Magnetic resonance imaging	25.48	10-37	23.49-27.46	28.82	11-47	26.92-30.72	0.019
	Nuclear medicine	2	0-6	1.54-2.46	2.47	0-6	2.08-2.86	0.13
All classes	Ultrasound	198.77	92-266	186.88-210.66	208.77	117-260	201.54-215.99	0.13
	Bone mineral densitometry	1.86	0-8	1.37-2.35	2.8	0-7	2.35-3.25	0.007
	Angiography	1.25	0-4	0.89-1.61	1.57	0-6	1.22-1.91	0.22
	Computed tomography	14.39	8-23	13.10-15.67	14.92	5-21	14.01-15.83	0.49
	Fluoroscopy	22.32	11-44	20.04-24.60	25.23	8-40	3.59-4.54	0.037
	Radiography	367.82	239-538	340.73-394.90	472.43	331-581	458.91-485.96	< 0.0001
	Magnetic resonance imaging	52.91	23-78	49.27-56.55	55.73	22-84	52.78-58.68	0.23
	Nuclear Medicine	2.61	0-8	2.01-3.21	3.5	0-7	3.05-3.95	0.017
	Ultrasound	271.55	149-346	258.11-284.98	291.77	184-350	283.07-300.46	0.010
	Bone mineral densitometry	2.68	0-9	2.03-3.33	4.07	0-8	3.59-4.54	0.001
Total		735.52	476-1024	693.13-777.91	869.22	553-1016	845.88-892.55	< 0.0001

10% and 37% in adult imaging volumes by modality during the first wave of the pandemic. Nuclear Medicine was the modality most impacted, and angiography the least impacted. While periods analysed may differ slightly, the findings for adult imaging volumes were less than those reported in Germany (41%, all modalities)[14], New York (14% to 53%)[15], California, Florida, Michigan, Massachusetts and New York (40% to 70%)[16], and Ohio (53%)[17]. During the second wave of the pandemic, all adult radiology modalities reported a reduction of between 2% and 32% in imaging volumes and between 9% and 24% in imaging volumes across all patient classes. Adult computed tomography imaging volumes experienced a 2% increase. Nuclear medicine was the modality most impacted. This is less than the data obtained from Medicare reported by Sreedharan *et al*[12], who found that general radiography and ultrasound were most impacted, while computed tomography and nuclear medicine services were less

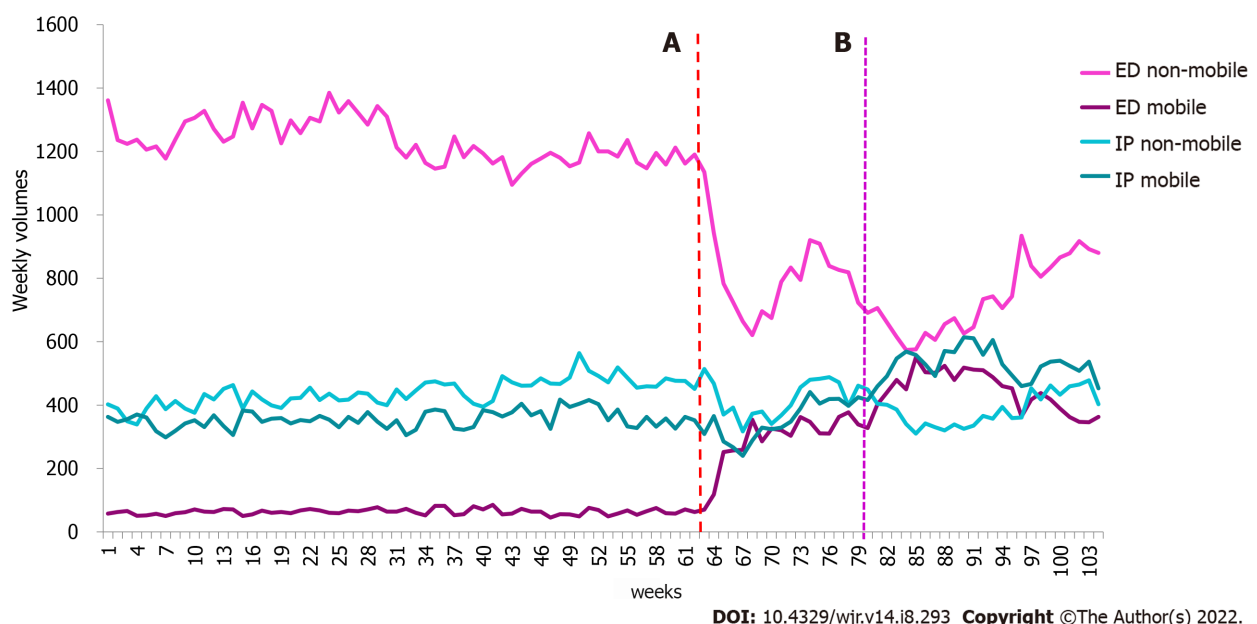
Table 12 Summed imaging volumes and percentage change in paediatric mobile imaging volume across patient class in waves 1 and 2

Wave 1	2020 (weeks 63-68)	2019 (weeks 11-16)	% change	Wave 2	2020 (weeks 80-95)	2019 (weeks 28-43)	% change
ED	44	32	37.5	ED	370	151	145.0
IP	400	415	-3.6	IP	1021	1340	-23.8
Overall	444	447	-0.7	Overall	1391	1491	-6.7

ED: Emergency department; IP: Inpatient.

Table 13 Comparison of mean paediatric weekly imaging volumes for 2019 and 2020 including 95% CIs, by mobile and non-mobile imaging categorised by patient setting

Paediatric Setting	Modality	2020			2019			P value
		Mean	Min-max	95%CI	Mean	Min-max	95%CI	
Emergency	Mobile	18.70	1-38	16.08-21.33	6.62	1-17	5.69-7.54	< 0.0001
	Non-mobile	142.07	63-251	126.62 - 157.52	199.97	121-261	192.12 - 207.81	< 0.0001
Inpatient	Mobile	66.89	44-95	63.13-70.64	72.95	46-102	69.31- 76.59	0.025
	Non-mobile	18.95	7-33	17.22-20.69	25.00	9-42	23.24-26.76	< 0.0001

**Figure 4 Weekly adult X-ray mobile and non-mobile imaging volumes from January 2019 to December 2020 (Weeks 1 to 104). A: Week 63-commencement of first wave; B: Week 80 commencement of second wave. ED: Emergency department; IP: Inpatient.**

affected. It was unclear whether paediatric data were included in their analysis[12].

Similarly, during the first wave of the pandemic, there was a reduction in paediatric imaging volumes of between 19% and 48% across all modalities except for angiography reporting a 50% increase in the imaging volume. There was a 4%-46% reduction across all paediatric patient classes. Nuclear Medicine was the modality most impacted, with ultrasound being the least impacted. While paediatric emergency patient presentations decreased by 25% in one Sydney health service, we observed a larger decrease in paediatric imaging service utilisation in the emergency department and inpatient settings[18].

During the second wave of the pandemic, there was a reduction of between 5% and 37% in paediatric modality cases and between 16% and 28% across paediatric patient classes. Nuclear Medicine was most impacted, while magnetic resonance imaging was least affected.

Decline in adult services (2% IP, 30% OP, 26% ED) were generally less to those reported by Naidich *et al*[15] (ED (27%), OP (57%), IP (14%)). Furthermore, outpatient services were reported in South Africa (40% over six months)[5]. outpatient imaging (58%, 72%[14,17], inpatient imaging (41%, 43%)[14,17],

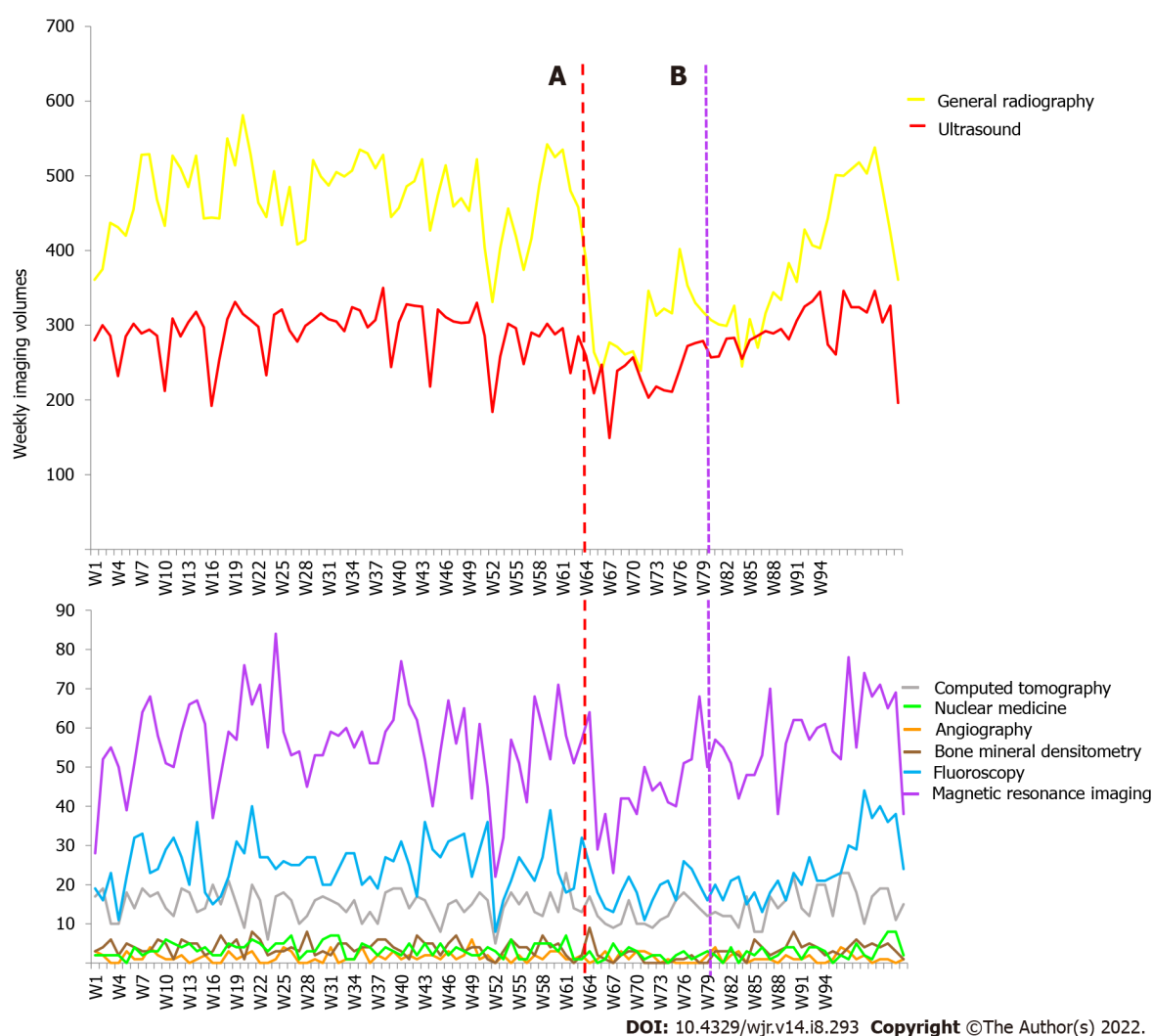


Figure 5 Weekly paediatric imaging volumes by modality from January 2019 to December 2020 (Weeks 1 to 104). A: Week 63-commencement of first wave; B: Week 80 commencement of second wave.

and emergency department imaging (39%, 49%)[14,17] in Ohio and Berlin highlighted greater declines in demands than we observed. Australia utilised the experience of other nations in preparation for COVID-19. For example, Australia reduced elective medical procedures in line with other countries and implemented PPE measures, social distancing, and stay-at-home measures for non-essential workers[5]. We found that most of our outpatient imaging services were severely impacted (19%-50% loss in imaging volume) by new social distancing and appropriate cleaning measures. Inpatient services were also affected by the decline in elective surgeries, while emergency patient volume was reduced due to more people isolating at home.

From July to September 2020, Australia experienced the pandemic's second wave. This was most prevalent in Victoria. The government implemented border closures, curfews, limiting movement to a five-kilometre radius, working from home for non-essential workers, business and education closures, wearing masks indoors and outdoors, and physical distancing measures to reduce COVID-19 cases[5]. During this phase of the pandemic, we observed a minor reduction in patient volume across all modalities at our institution compared to the first wave's impact. This could be due to health services becoming better equipped, informed and organised to manage pandemic outbreaks[5]; earlier diagnosis of COVID-19 *via* more rigorous PCR testing[5,20]; patients were better informed about the risks of contracting COVID-19, thus more likely to seek medical care. Earlier in the pandemic, it had been reported that patients were afraid to come to the hospital, potentially compromising their health[21,22].

Angiography

Our angiography statistics represented interventional radiology procedures performed in the angiography suite primarily guided by fluoroscopy or ultrasound. Like other modalities, the angiography suite was substantially impacted in outpatient volume when the Department of Health and Human Services ruled that only Category 1 patients could attend. In April and August 2020, there was a decrease in inpatient studies. However, recovery in this patient class was swift, with patient

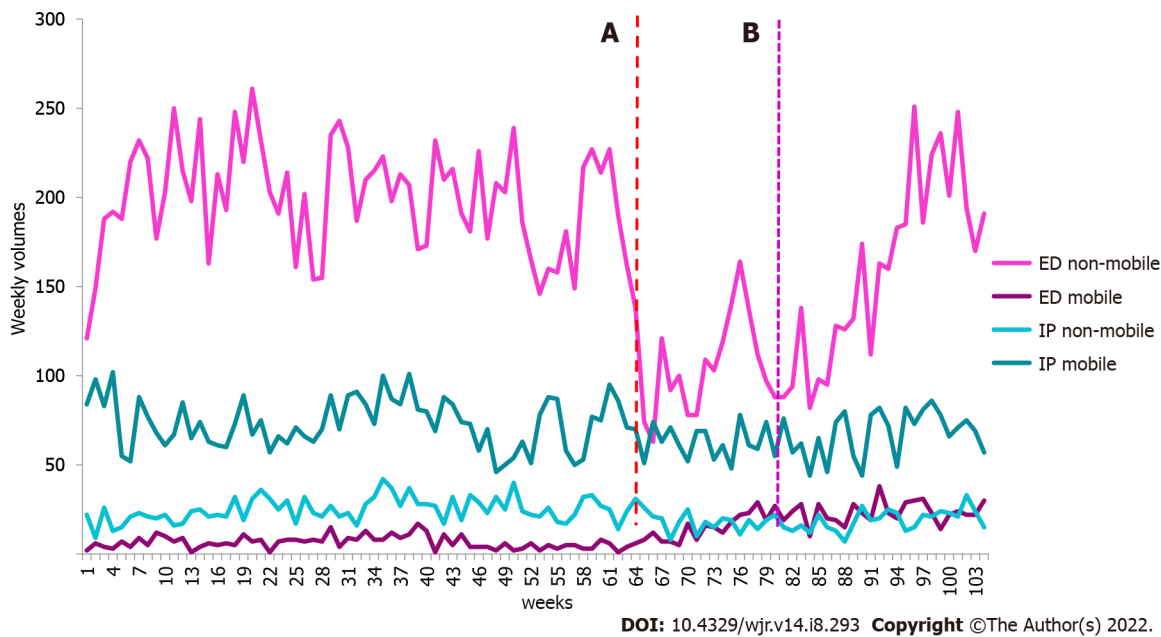


Figure 6 Weekly paediatric X-ray mobile and non-mobile imaging volumes from January 2019 to December 2020 (Weeks 1 to 104). A: Week 63-commencement of first wave; B: Week 80 commencement of second wave. ED: Emergency department; IP: Inpatient.

volume surpassing pre-COVID attendances. Patients delayed procedures during the first wave of COVID-19 for fear of contracting the virus while in hospital.[7] This increased unplanned hospital admissions with patients requiring procedures, leading to increased service demand. Some patients may have also been scheduled to relieve burgeoning waitlist times.

Bone mineral densitometry

United Kingdom bone mineral densitometry (BMD) wait lists increased during the pandemic, resulting in treatment delays for osteoporosis[23]. We observed the same relative reduction in imaging volumes during the first and second waves of the pandemic, likely determined by clinic closures[24], use of telehealth to minimise hospital visits[5], staff redeployment[25], or delaying medical treatment[26].

CT

CT was one of the modalities least impacted by new policies and guidelines implemented during the pandemic. This is not surprising given the importance of CTPA for early contribution to patient diagnosis[5]. While early in the pandemic, CT was the modality of choice for assisting in COVID-19 diagnosis[5], this changed due to the high radiation doses and availability of PCR testing[5]. While there was a reduction in CT demand during the peak waves of the pandemic, we observed an increase in CT utilisation during the second wave of the pandemic, consistent with other reports[27]. During the pandemic, outpatient CT studies for malignancy staging were delayed based on criteria set by senior management due to the risk of cross-contamination between inpatients and outpatients. Access to an independent CT scanner within the hospital at an onsite research facility improved workflow for this patient cohort. During the pandemic, elderly Victorians in aged care died from the virus as transmission rates among staff members in certain aged care facilities increased. The government intervened by placing aged care residents into Victorian hospitals as a safety measure for our most vulnerable. The increase in inpatient CT scans during this period can likely be attributed to this mandate.

Fluoroscopy

Many non-clinically urgent fluoroscopy studies, such as barium swallows for outpatient studies, were placed on hold or rescheduled during the pandemic. Following Victoria's second wave, there was a resurgence of patient bookings from October 2020. The end of September 2020 marked the easing of stage 4 restrictions, with COVID-19 infections decreasing significantly. Thus outpatient and inpatient bookings were rescheduled over the coming months to cope with demand. A significant change in imaging volume was observed between June and July, with a below-average patient number in July (Figure S2). This can be likely attributed to the similar timing of outbreaks in COVID-19 at aged care centres, prompting the Victorian government to move aged care residents to hospitals to prevent further COVID-19-related deaths.

General radiography

While adult general X-ray was particularly impacted during the pandemic's first wave, likely due to the cancellation of elective surgery and outpatient clinics, less impact was observed during the second wave. Conversely, paediatric general X-ray imaging volumes significantly reduced during both pandemic waves. In 2020, the utilisation of mobile imaging saw significant growth. This can be attributed to workflow changes such as infection control measures to reduce patient movement[28]. Senior management purchased extra mobile imaging systems to manage the increased demand, contributing to the observed changes. Other imaging protocol modifications to reduce the risk of contracting COVID-19, such as imaging through glass, were performed but not used routinely at our institution[8]. The utilisation of mobile imaging more than doubled during the peak of the pandemic at our institution, particularly in the emergency setting. This is comparable with the findings of others. Surveyed Western Australian medical imaging professionals perceived increased mobile chest imaging, particularly in the public hospital setting[29]. At the same time, in Singapore, there was a three-fold increase in emergency department mobile imaging usage[30]. Although mobile imaging utilisation increased, there was little change in radiographer-reported doses[31]. There was a slight shift in imaging regions other than the chest (data not shown)[31]. We also observed that fixed X-ray imaging decreased when adult mobile imaging increased in the emergency setting. This was likely to reduce transmission risk and manage potential increased demand[8,32]. The greatest impact on adult mobile imaging usage was observed during the pandemic's second wave, when the risk of cold and influenza was heightened (July-September 2020)[33].

MRI

We observed appreciable declines due to work practice changes implemented in adult and paediatric MRI services during the pandemic contributed to long waiting lists across our network. Elective general anaesthetic cases were placed "on hold" as per Victorian Government recommendations and aerosol-generating procedure policies to allow room resting and cleaning that extended the total examination time, particularly impacted paediatric services[3,34,35].

Mammography

As with other imaging modalities, our mammography service also experienced a reduction in imaging volumes during the first and second waves of the pandemic. This is consistent with other findings, though to a lesser extent, in our health service[15,36,37]. In Australia, breast screening services were temporarily suspended, with services reopening based upon government recommendations. Similarly, changes in workflow required stricter patient management protocols and cleaning protocols to minimise transmission risk[28,37,38].

Nuclear medicine

We found that nuclear medicine, then mammography were the modalities most impacted by the pandemic and consistent with the findings of others[15,16,36,37]. This could, in part, be due to logistical changes to isotope supply. From March to July and October to November 2020, there were significant issues with isotope transportation locally and overseas, particularly during the first wave of the pandemic. Due to unforeseen mechanical problems at the Australian Nuclear Science and Technology Organisation manufacturing site, there were also supply interruptions. These included a broken conveyor belt, storm causing electrical faults, production failure, isotope refinement and contamination issues. Other challenges included scheduled reactor shutdown, with difficulty in alternate isotope sourcing to meet demand. These interruptions could have contributed to the significant changes observed.

Ultrasound

At our institution, ultrasound was less impacted than other modalities, which is consistent with other experiences[16,19]. However, data from Germany found ultrasound was the most significantly affected imaging modality, though not all modalities were included in their analysis[14]. Ultrasound services were transformed considerably in the early weeks of the outbreak, with the expansion of ambulatory centres to provide 'clean' sites. In the main hospital centres, there was a substantive need for mobile ultrasound examination both in ED and in the wards. In the lead-up to the pandemic, we observed a decrease in ED patients. ED patient imaging volume stabilised during the pandemic, with some growth observed. The reason for this surge was thought to be multi-factorial. There seemed to be a tendency for patients to attend an ED rather than their local GP. It was also believed that patients' examinations were initially delayed, and the surge compensated for this. There was no obvious change in the referral patterns for the types of examinations requested. Anecdotally, point of care ultrasound (PoCUS) examinations decreased across this period. This seemed to be related to clinicians minimising patient contact and deciding to suspend PoCUS training.

Inpatient services overall increased, but there were small reductions in patient volumes during the first and second waves. While other services reported some value for lung ultrasound, this was not used in evaluating COVID-19-positive patients at our institution[10]. Consistent with the other modalities, we

did see a decrease in outpatient attendances, which returned relatively quickly. This is likely due to outpatient clinic closures, halting non-essential ultrasound intervention, and patients' choice to delay their scans. As with other modalities, ultrasound was less impacted during the second wave. Obstetric cases throughout this period were deemed an essential service and did not change. Sonographers were activated to perform blood pressures as part of a third-trimester pathway as many women were seen *via* telehealth. The Early Pregnancy Bleeding pathway and clinic were also relocated to ultrasound. Minor changes were made to scan protocols. Targeted scans were introduced for high-risk patients. The timing of paediatric hip screening was adjusted to minimise the risk of repeat examinations.

Paediatrics

Overall, there was a decrease of approximately 55% from April to October 2020 compared to 2019. Recovery of paediatric imaging, particularly after the second wave (September to December 2020), was more rapid, coinciding with the gradual reduction in Melbourne's COVID-19 case numbers and the subsequent easing of restrictions. Many patients and families deferred non-urgent imaging during the lockdown. Moreover, lockdown, home-schooling and suspension of group sports further reduced paediatric cases from sporting injuries[39]. We did observe a slight increase in some services, such as MRI, during 2020 despite COVID-19 disruption, as services returned to pre-COVID-19 demand. This was due to the new software and hardware upgrade in February 2020, reducing the total scan time and potentially increasing patient throughput while providing additional time for cleaning. As observed with adult modality data, following lockdowns in April and July-September 2020 and elective surgery deferral, there was a dramatic decrease in paediatric imaging across all modalities, except for angiography (minimal imaging volume). Recovery was observed between the first and second waves. However, it did not reach the pre-COVID-19 Levels. We also observed an increase in mobile usage in emergencies to help reduce the transmission risk.

Study limitations

While our health service cared for the first Australian COVID-19 patient, other health services across Melbourne, particularly in the north and west, experienced higher caseloads. Consequently, these health services may have experienced more significant declines in radiology services than we observed across our health services. Our institution purchased additional mobile X-ray units to prepare for the pandemic, contributing to the increased use. Of note, the MRI software and hardware upgrades did not significantly increase the imaging volume. However, they did provide additional time for practice changes, such as improved infection control measures. Nuclear medicine experienced even more significant challenges during the pandemic due to unforeseen interruptions to isotope supplies as a confounding variable. This required additional patient rescheduling, often at short notice. Given that data was analysed between 2019 and 2020, some underlying baseline year-to-year variability may be contributing to the findings. Timeframes defining COVID-19 may vary worldwide, making data comparison somewhat difficult.

This work represents one large Victorian health service; however, it may not be generalisable to other health services.

Lessons learned: (1) Once-in-a-lifetime events such as a global pandemic can significantly impact workflow across imaging modalities, with the need to implement new processes; (2) Our experience during the pandemic was not the same as those experiences described by other nations due to the variation in severity and (3) Modalities across our health network were impacted differently due to changes in service demands, closures of outpatient clinics, and rescheduling elective surgeries.

CONCLUSION

Collected data provides an evidence-based insight into changing imaging volume related to COVID-19. This information will allow the network to predict the dynamic demands in imaging more accurately and promptly adapt its policies. We found that adult CT, angiography and ultrasound recovery following the first and second waves of the pandemic recovered faster than nuclear medicine, BMD and MRI. Paediatric MRI and ultrasound recovered faster than nuclear medicine and general radiography following the first and second waves of the pandemic. Modalities were less impacted during the second wave (July-September 2020) than during the first wave (April 2020), except for angiography outpatients. At our health network, nuclear medicine was the imaging modality most impacted by COVID-19 in adult and paediatric settings. There may have been other factors, however, influencing these results. Adult CT imaging increased during the second wave, while paediatric ultrasound was the least affected. Radiology departments can minimise the impact of future COVID-19/public health outbreaks on imaging volumes by ensuring each modality is appropriately resourced to continue providing safe and patient-centred care.

ARTICLE HIGHLIGHTS

Research background

Medical imaging modalities worldwide were significantly impacted by the the coronavirus disease 2019 (COVID-19) pandemic; however, each country's experience differed. This study provides an in-depth analysis of the impact on adult, paediatric, inpatient, outpatient, emergency and mobile services across the first and second waves of the COVID-19 pandemic in a large public health network in Victoria, Australia.

Research motivation

This work provides evidence for managing and redeploying resources during "once in a lifetime" events such as a pandemic and impact duration. Using this work, modelling and forecasting anticipated changes to imaging demand can be performed, allowing optimal utilisation of departmental staffing to manage workloads.

Research objectives

To identify adult and paediatric imaging volume changes, including mobile imaging across a large Victorian public hospital network. We realised our objectives, and the findings highlighted significant differences across the modalities analysed. Future research could monitor the long-term impacts of such events, such as staff burnout or opportunities for additional training to address deficiencies identified.

Research methods

The use of statistical methods in data analysis highlighted the modalities, patient classes and differences between adult and paediatric imaging. Particularly, methods to identify any correlation between mobile and non-mobile imaging volumes were novel.

Research results

We identified that the greatest impact occurred in Nuclear Medicine during the first and second waves, with all modalities less affected during the second wave; other modalities such as computed tomography were less impacted, requiring greater resources to manage service demand. We observed a shift in regions imaged using mobile imaging. It would be essential to understand this impact regarding image quality, workflow and patient radiation dose.

Research conclusions

Medical imaging modality services across a large Victorian public health network were significantly affected during the COVID-19 pandemic; however, the impact on different modalities varied relative to studies performed in other countries. It is essential to have a broad perspective of the impact to each imaging modality in both the adult and paediatric context to help better address the need for workflow changes. It is essential to consider whether imaging services are inversely correlated to manage optimal departmental resourcing.

Research perspectives

Future research could further investigate the long-term impact of lockdowns and the pandemic on imaging modality volumes and their recovery. This can help inform future budgeting requirements regarding the need for additional equipment and staffing to manage continuous workflow demands.

FOOTNOTES

Author contributions: Pinson JA, Badawy MK, designed and coordinated the study; Pinson JA, Badawy MK, Diep ML, Krishnan V, Aird C, Cooper C, Leong C, Chen J, Paul E and Ardley N performed the data collection, analysed and interpreted the data; Pinson JA, Badawy MK, Diep ML, Krishnan V, Aird C, Cooper C, Leong C, Chen J, Paul E and Ardley N wrote the manuscript; all authors have read, edited and approved the final version of the manuscript.

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Informed consent statement: Patients were not required to give informed consent to the study because the analysis used anonymous clinical data that were obtained after each patient agreed to treatment by written consent. For full disclosure, the details of the study are published on the home page of Fukushima Medical University.

Conflict-of-interest statement: We have no financial relationships to disclose.

Data sharing statement: Technical appendix, statistical code, and dataset available from the corresponding author at

mohamed.badawy@monashhealth.org.

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Country/Territory of origin: Australia

ORCID number: Jo-Anne Pinson 0000-0001-6654-0278; My Linh Diep 0000-0001-5007-3046; Vinay Krishnan 0000-0002-0062-5348; Caroline Aird 0000-0002-3942-4375; Cassie Cooper 0000-0001-8504-8086; Christopher Leong 0000-0001-9496-799X; Jeff Chen 0000-0003-4553-9221; Nicholas Ardley 0000-0002-2251-8754; Eldho Paul 0000-0003-1263-7255; Mohamed Khaldoun Badawy 0000-0001-8029-9951.

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