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Defining Radiation Treatment Interruption Rates During the COVID-19 Pandemic: Findings From an Academic Center in an Underserved Urban Setting

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Purpose: Our purpose was to characterize radiation treatment interruption (RTI) rates and their potential association with sociodemographic variables in an urban population before and during the COVID-19 pandemic.

Methods and Materials: Electronic health records were retrospectively reviewed for patients treated between January 1, 2015, and February 28, 2021. Major and minor RTI were defined as ≥5 and 2 to 4 unplanned cancellations, respectively. RTI was compared across demographic and clinical factors and whether treatment started before or after COVID-19 onset (March 15, 2020) using multivariate logistic regression analysis.

Results: Of 2,240 study cohort patients, 1,938 started treatment before COVID-19 and 302 started after. Patient census fell 36% over the year after COVID-19 onset. RTI rates remained stable or trended downward, although subtle shifts in association with social and treatment factors were observed on univariate and multivariate analysis. Interaction of treatment timing with risk factors was modest and limited to treatment length and minor RTI. Despite the stability of cohort-level findings showing limited associations with race, geospatial mapping demonstrated a discrete geographic shift in elevated RTI toward Black, underinsured patients living in inner urban communities. Affected neighborhoods could not be predicted quantitatively by local COVID-19 transmission activity or social vulnerability indices.

Conclusions: This is the first United States institutional report to describe radiation therapy referral volume and interruption patterns during the year after pandemic onset. Patient referral volumes did not fully recover from an initial steep decline, but local RTI rates and associated risk factors remained mostly stable. Geospatial mapping suggested migration of RTI risk toward

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marginalized, minority-majority urban ZIP codes, which could not otherwise be predicted by neighborhood-level social vulnerability or pandemic activity. These findings signal that detailed localization of highest-risk communities could help focus radiation therapy access improvement strategies during and after public health emergencies. However, this will require replication to validate and broaden relevance to other settings. © 2022 Elsevier Inc. All rights reserved.

Introduction

Public health responses to the COVID-19 pandemic (eg, social distancing and local “stay at home” orders) and patient treatment avoidance severely compromised cancer care in the United States (US) and abroad. There has been well-documented deferment of cancer screenings and diagnoses since the beginning of the pandemic as well as significant reduction in cancer-related clinical encounters among patients actively on treatment. A British study leveraging the United Kingdom Health Data Research Hub for Cancer registry to survey changes in cancer service utilization and outcomes during the early pandemic demonstrated an increase in cancer-related deaths independent of COVID-19 infection during the first pandemic year. Given ongoing waves of variant-driven pandemic spread, there remains urgent need to balance prevention of infection while maintaining cancer treatment continuity and quality. Unplanned interruption of daily radiation therapy (RT) disproportionately affects marginalized populations. Expected survival outcomes incrementally decrease with each day of interruption. Because the pandemic broadly handicapped cancer treatment quality measures, we wished to inquire whether COVID-19 widened baseline RT access disparities. This is particularly relevant to the Southeastern US, where COVID-19 transmission rates have led the nation. Reliability characterization of RT interruption (RTI) rates in the United States during the pandemic remains unavailable. A published survey of national radiation oncology practice leaders sponsored by the American Society of Radiation Oncology suggested that patients have presented to community-based care with more advanced stage disease and have experienced frequent treatment interruptions during the pandemic. Early international series from acutely affected centers in Asia and Italy reported abrupt increases in RTIs and access delays in spring 2020, but these experiences were not supplemented by longitudinal follow-up. A more recent series from India suggested higher RTI rates during COVID-19 at a tertiary center because of government-instituted transportation “curfews,” although the study cohort was limited to 76 patients with head and neck cancer. The intent of this report was to compare RTI rates in a metropolitan population treated before and after onset of the pandemic at a US academic center over a calendar year and to characterize associations between RTI, clinical factors, patient demographics, and home neighborhood location.

Methods and Materials

Patient population

Institutional review board approval (#16-04888-XP and #20-07287-XM) was granted to retrospectively review electronic health records (EHRs) for all patients treated with RT at our academic inner urban safety-net hospital practice from January 1, 2015, to March 14, 2020, for prepandemic benchmarking, and March 15, 2020, to February 28, 2021, after the recognized onset of COVID-19 in our city. Patients whose treatments spanned the March 15, 2020, cut point were included in the pre—COVID-19 cohort. Due to a turnover in medical school-hospital partner affiliation and radiation oncology EHR systems, complete records were not available for all patients treated from January 2018 to May 2019. This interval was excluded from analysis. Patients who did not initiate treatment at our facility were also excluded from study.

Outcome measures

RTI was defined as an unplanned treatment cancellation or patient “no-show.” Our primary outcome measure was major RTI, defined as greater than or equal to 5 interruptions during the prescribed course of treatment. Minor RTI was defined as 2 to 4 RT schedule interruptions. Scheduled interruptions occurring on a day the clinic was closed (ie, holidays) were not counted. Only interruptions occurring after the start date of treatment were included for analysis.

Data collected

Clinical and treatment information in addition to demographic information such as patient residence addresses were collected. Patient addresses were used for mapping at the ZIP code level to maintain patient privacy. For health insurance status, patients were categorized as either uninsured or enrolled in Medicaid versus patients insured commercially or with Medicare without dual coverage status. Predicted income was categorized as low, middle, or high using 2020 US Census data for patient’s home address ZIP code (<$34,000, $34,001 to $67,000, and >$67,000, respectively). Distance from patient’s residence to the RT facility was calculated using the patient’s address.

Statistical analysis

Significance of differences in distribution of patient characteristics between treatment eras was examined with $\chi^2$ test-
ing. We tested for differences between 2 Poisson rates\textsuperscript{25} to determine significance of decreases in patients starting RT for each calendar month, as well as changes in distribution of disease site presentations after the start of COVID-19 versus baseline data from the prior cataloged year. We adjusted for multiplicity in testing by Bonferroni correction: $P = .05/12 = .0042$ for monthly starts (controlling for a family-wide error rate at 5%) and $P = .05/10 = .005$ for each of 10 site categories. Major and minor RTI rates were calculated according to any treatment given relative to the beginning of the local COVID-19 public health emergency on March 15, 2020. Frequencies of variables were calculated according to RTI status and treatment timing. Multivariable logistic regression models were built to determine the effect of each variable on interruption rates in each era. Our modeling strategy used a stepwise process to adjust the effect of variables on interruption rates in terms of population characteristics. Variables were retained in the model using a variable inclusion threshold $P$ value of $< .1$ on Wald’s test.

The effect of timing relative to the pandemic on each variable was also investigated with multivariable logistic regression models, which included an interaction term between treatment period (before or during COVID-19) and each variable. This model was defined as

$$\log \left( \frac{\text{major/minor interruption}}{\text{no major/minor interruption}} \right) = \beta_0 + \beta_1 \times \text{variable} + \beta_2 \times \text{era} + \beta_3 \times \text{variable} \times \text{era}$$

The effect of treatment period in different categories of each variable was tested with the interaction effect of treatment period and variable. Odds ratios (ORs) and 95% confidence intervals were reported. Statistical analyses were conducted with R Studio (version 1.2.5033) software, with $P$ values $< .05$ being considered statistically significant.

Geospatial analysis

Frequency of RTI was mapped at the level of residence ZIP codes and stratified according to patient race and insurance status. Mapping was performed with RStudio version 1.3.959 (PBC, Boston, MA) using the geospatial (GIS) package ggmap. Spatial visualization was performed with the GIS package ggplot2. Individual COVID-19 test results were geocoded by self-reported patient home address from a Health Insurance Portability and Accountability Act (HIPAA)—compliant institutional COVID-19 testing registry (#20-07287-XM) managed by the senior author, which collected data from all local health department-supported outpatient COVID-19 testing. Social vulnerability index (SVI)\textsuperscript{26} and COVID-19 transmission mapping were performed with ArcGis Pro version 2.8.6 (Redlands, CA), using data obtained from our COVID-19 registry as well as the current subscription version of the national PolicyMap database.\textsuperscript{27} The SVI data set included rank (categorical) and score (continuous) data. SVI rank has been used for data visualization, whereas SVI score has been used in GIS statistical analysis. Because the SVI data set is available at either census tract or county level, SVI ranks and scores for each ZIP code in the study area were estimated from census tract level data by land-area based geoiimputation method.\textsuperscript{28} ZIP codes containing $\geq 50\%$ “moderate” or “high” SVI US Census tracts were designated as “high SVI.” Local bivariate relationship (LBR) analysis was used to test for spatial association between RTI, COVID-19 incidence, and estimated SVI score distribution within our study area. LBR tests whether 2 variables share a statistically significant relationship throughout the space using local entropy.\textsuperscript{29} $P$ values were calculated through a permutation test with $\alpha = .05$ as the level of statistical significance. The false discovery test was used to account for multiple testing. Mean $P$ values were also calculated by the LBR statistics to show whether there were statistically significant relationships between the variables throughout the study area. LBR analysis was performed with ArcGIS Pro.\textsuperscript{30}

Results

Study cohort

A total of 2,240 patients received RT at our center and were included for analysis. Before March 15, 2020, 1,938 patients started treatment, and the remaining 302 patients began treatment afterward. Descriptive cohort characteristics across prepandemic and COVID-19 periods are presented in Table 1. For the full study population, median age was 61.8 years (19.7-95.7), and 1,172 (52%) subjects were female, similar across treatment periods. Our clinic serves a racial minority-majority population. Black patients constituted 57% (1,281) of the full cohort: 1,098 (57%) at baseline and 183 (61%) during the pandemic. There was no detectable population-level shift of patients from rural to urban neighborhoods close to our clinic; similar numbers of patients lived within 0 to 10 miles during the pandemic (57%) relative to before (54%). There were significant differences ($P < .05$) between baseline and pandemic cohorts in proportions of underinsured patients, married patients, and primary disease sites. Ninety-one (30%) patients treated during the pandemic were uninsured or enrolled on Medicaid versus 364 (19%) at baseline.

Patient census and case mix after onset of COVID-19

On-treatment patient census fell 49% the month immediately after onset of the pandemic and 36% over the first year of the pandemic. Fluctuating, incomplete recovery of patient referral volume was observed through to the spring of 2021 (Fig. 1A). A significant reduction in the number of patients
|                | Total | Pre—COVID-19 era | COVID-19 era |
|----------------|-------|------------------|--------------|
|                | n (%) | n (%)            | n (%)        |
| Total patients | 2240  | 1938 (86.5)      | 302 (13.5)   |
| Sex            |       |                  |              |
| Female         | 1172  | 1013 (52.3)      | 159 (52.7)   |
| Male           | 1068  | 925 (47.7)       | 143 (47.4)   |
| Age (mean, y)  |       |                  |              |
| <65            | 1380  | 1198 (61.8)      | 182 (60.3)   |
| ≥65            | 860   | 740 (38.2)       | 120 (39.7)   |
| Race           |       |                  |              |
| Black          | 1281  | 1098 (56.7)      | 183 (60.6)   |
| White          | 827   | 725 (37.4)       | 102 (33.8)   |
| Unknown        | 109   | 97 (5.0)         | 12 (4.0)     |
| Other race     | 23    | 18 (0.9)         | 5 (1.7)      |
| Marital        |       |                  |              |
| Married        | 879   | 773 (39.9)       | 106 (35.1)   |
| Single         | 595   | 525 (27.1)       | 70 (23.2)    |
| Widowed        | 253   | 258 (13.3)       | 53 (17.6)    |
| Divorced       | 305   | 200 (10.3)       | 47 (15.6)    |
| Separated      | 105   | 90 (4.6)         | 15 (5.0)     |
| Unknown        | 30    | 19 (1.0)         | 11 (3.6)     |
| Predicted annual income |       |                  |              |
| Low (<$34,000) | 821   | 704 (36.3)       | 117 (38.7)   |
| Middle ($34,000-$67,000) | 938 | 807 (41.6)       | 131 (43.4)   |
| High ($67,000) | 255   | 223 (11.5)       | 32 (10.6)    |
| Unknown        | 226   | 204 (10.5)       | 22 (7.3)     |
| Insurance type |       |                  |              |
| Medicare       | 940   | 813 (42)         | 127 (42.1)   |
| Commercial     | 840   | 757 (39.1)       | 83 (27.5)    |
| At risk (Medicaid/no insurance) | 455 | 364 (18.8)       | 91 (30.1)    |
| Other          | 5     | 4 (0.2)          | 1 (0.3)      |
| Fractions      |       |                  |              |
| 1–20           | 1044  | 899 (46.4)       | 145 (48.0)   |
| >20            | 1196  | 1039 (53.6)      | 157 (52.0)   |
| Diagnosis      |       |                  |              |
| Breast         | 408   | 341 (17.6)       | 67 (22.2)    |
| H&N            | 338   | 275 (14.2)       | 63 (20.9)    |
| Metastasis     | 370   | 319 (16.5)       | 51 (16.9)    |
| Lung           | 271   | 237 (12.2)       | 34 (11.3)    |
| Prostate       | 169   | 144 (7.4)        | 25 (8.3)     |
| GI             | 199   | 174 (9.0)        | 25 (8.3)     |
| GYN            | 134   | 122 (6.3)        | 12 (4.0)     |
| Hematologic    | 99    | 85 (4.4)         | 14 (4.6)     |

(Continued)
starting RT was observed during April (P = .004), June (P < .001), and October (P < .001) of 2020, all of which took place during local pandemic surges. A trend toward differences was seen for May (P = .01), July (P = .01), and September (P = .06) of 2020 and January of 2021 (P = .06).

Total number of patients starting RT was significantly different between eras (P < .001). Distribution of primary disease site by COVID-19 era is presented in Fig. 1B. Significant differences were observed during COVID-19 in number of central nervous system (P < .001) and “other” primaries (P = .005). A trend toward differences was seen for breast (P = .01) and head and neck (P = .009).

### RT interruption rates before and during COVID-19

For the entire study cohort, 1,187 (53%) patients completed RT without interruption. Three hundred eighty-nine (17%) patients missed 1 appointment, 396 (18%) patients missed 2 to 4, and 264 (12%) missed 5 or more RT appointments. Mean RT interruption was 1.9 days (standard deviation [SD], 4) with a maximum of 42 days. The median number of missed appointments was 9 (mean, 10.7; SD, 6.5) and 2 (mean, 2.6; SD, 0.7) for patients who experienced either major or minor interruptions, respectively. Out of a total of 47,514 prescribed fractions, 46,334 (97.5%) treatments were delivered. At prepandemic baseline, 40,121 (97%) of 41,192 prescribed fractions were received. During the pandemic, 6213 (98%) out of 6,322 prescribed fractions were delivered.

RTI rates were incrementally lower during the pandemic (Table 2), although this remained nonsignificant for both major (OR, 0.73; 0.47-1.09; P = .14) and minor (OR, 0.81; 0.56-1.13; P = .23) interruptions. Association of baseline versus COVID-19-era treatment with potential RTI risk factors was modest (Tables E1 and E2). Before the pandemic, 1,357 (70%) patients completed RT with 0 to 1 interruption, 349 (18%) experienced 2 to 4 days of delay, and 232 (12%) patients had 5 or more interruptions. During COVID-19, 223 (73%) patients completed their radiation treatment with 0 to 1 interruption, 47 (16%) experienced 2 to 4 interruptions, and 32 (11%) were affected by major RTI during COVID-19. Of the 516 individual interruption events observed during COVID-19, 164 (32%) were due to a patient “no-show” versus 1,154 (31%) of the 3,738 total RTI events observed before the pandemic. From treatment records, only 1 patient was noted to have treatment interrupted directly by active COVID-19 infection. This was a patient receiving adjuvant RT, with the final week of treatment postponed 10 days by patient self-isolation.

### Association of population characteristics with RTI rates

Results from unadjusted and adjusted modeling of associations between risk factors and major/minor RTI rates are presented in Tables 3 and 4, respectively. On univariate logistic regression analysis, most risk factors (eg, age <65, Black race, nonmarried status, Medicaid or no insurance

| Table 1 (Continued) | Total n (%) | Pre—COVID-19 era n (%) | COVID-19 era n (%) |
|----------------------|-------------|------------------------|---------------------|
| CNS                  | 102 (4.6)   | 99 (5.1)               | 3 (1.0)             |
| Other                | 148 (6.6)   | 140 (7.2)              | 8 (2.7)             |
| Unknown              | 2 (0.1)     | 2 (0.1)                | -                   |
| Distance to RT in miles |                |                        |                     |
| 0-5                  | 600 (26.8)  | 507 (26.2)             | 93 (30.8)           |
| 5-10                 | 613 (27.4)  | 534 (27.6)             | 79 (26.2)           |
| 10-15                | 338 (15.1)  | 292 (15.1)             | 46 (15.2)           |
| 15-20                | 104 (4.6)   | 90 (4.6)               | 14 (4.6)            |
| 20-30                | 98 (4.4)    | 84 (4.3)               | 14 (4.6)            |
| 30-40                | 78 (3.5)    | 69 (3.6)               | 9 (3.0)             |
| >40                  | 194 (8.7)   | 169 (8.7)              | 25 (8.3)            |
| Unknown              | 215 (9.6)   | 193 (10.0)             | 22 (7.3)            |
| RT start month       |              |                        |                     |
| Nonwinter (March-October) | 1440 (64.3) | 1239 (63.9)            | 201 (66.6)          |
| Winter (November-February) | 800 (36.7) | 699 (36.1)             | 101 (33.4)          |

P = P value from test for trend. Multivariable logistic regression model C-statistic = 0.71.

Abbreviations: CNS = central nervous system; GI = gastrointestinal; GYN = gynecologic; H&N = head and neck; RT = radiation therapy.

* Statistically significant (Bonferroni-adjusted P < .0001).
coverage, prescribed treatment longer than 20 fractions, treatment in winter months [November-February], and travel distance to treatment less than or equal to 10 miles) were associated with increased major RTI risk before COVID-19. This association held during COVID-19 for Medicaid covered or patients with no insurance, nonmarried, or receiving >20 fractions. On univariate analysis, age <65, treatment longer than 20 fractions, and treatment in winter months were associated with increased minor RTI risk at baseline. During COVID-19, only treatment in winter months remained significantly associated with minor RTI.

On multivariate modeling, patients with Medicaid coverage or no insurance experienced higher rates of major RTI compared with patients insured commercially or through Medicare both at baseline (OR, 1/0.44 = 2.27; P < .01) and during COVID-19 (OR, 1/0.38 = 2.63; P = .02). Patients prescribed >20 fractions experienced 6.47 times higher risk (P < .01) for major RTI in the pre-COVID-19 era and 3.58 times higher risk (P < .01) during the pandemic. Treatment in winter (P < .01) and traveling <10 miles to treatment (P = .02) were associated with higher major RTI only at baseline. Age, sex, race, and predicted income were not associated with major RTI, although nonmarried status trended toward association with major RTI during COVID-19 (P = .06).

With respect to minor interruptions, age <65 (P < .01), treatment >20 fractions (P < .01), and a winter start (P < .01) were associated with higher RTI rates at baseline on multivariate analysis. Although nonmarried status (P = .08) and Black race (P = .09) trended toward associations with increased minor RTI rates during the pandemic, only winter start remained significant (P < .01).

**Interaction between timing of treatment and interruption risk factors**

As noted previously, interaction of treatment timing relative to COVID-19 with potential RTI risk factors was modest and was limited to minor interruptions. Specific interactions with variables are summarized for RTI rates in Tables E1 and E2. Although Medicaid/uninsured insurance status (P
### Table 2  RT interruption rates by patient characteristic

|                          | Total          | Pre—COVID-19 era | COVID-19 era |
|--------------------------|----------------|------------------|--------------|
|                          | Minor interruption (%) (2-4 RT breaks) | Major interruption (%) (5+ RT breaks) | Minor interruption (%) (2-4 RT breaks) | Major interruption (%) (5+ RT breaks) |
| Overall                  | 20.0           | 11.8             | 20.5         | 12.3         | 17.4 | 10.6 |
| Sex                      |                |                  |              |              |      |      |
| Female                   | 19.7           | 11.9             | 20.2         | 12.3         | 16.6 | 8.8  |
| Male                     | 20.5           | 11.7             | 20.8         | 11.6         | 18.4 | 12.6 |
| Age (mean, y)            |                |                  |              |              |      |      |
| <65                      | 22.4           | 14.0             | 23.1         | 14.2         | 18.2 | 12.6 |
| ≥65                      | 16.5           | 8.3              | 16.5         | 8.4          | 16.2 | 7.5  |
| Race                     |                |                  |              |              |      |      |
| Black or African American| 21.4           | 13.7             | 21.5         | 14.0         | 20.5 | 12.0 |
| White                    | 18.3           | 9.4              | 19.0         | 9.4          | 13.0 | 9.8  |
| Unknown                  | 20.6           | 6.5              | 21.1         | 7.2          | 16.7 | -    |
| Other race               | 10.0           | 13.0             | 13.3         | 16.7         | 0.0  | -    |
| Marital                  |                |                  |              |              |      |      |
| Married                  | 17.6           | 8.9              | 18.4         | 9.4          | 11.9 | 4.7  |
| Single                   | 21.9           | 14.6             | 23.0         | 15.4         | 14.1 | 8.6  |
| Widowed                  | 18.9           | 14.2             | 16.6         | 12.5         | 28.6 | 20.8 |
| Divorced                 | 24.8           | 10.2             | 24.6         | 10.1         | 26.2 | 10.6 |
| Separated                | 23.2           | 21.9             | 26.8         | 21.1         | 0.0  | 26.7 |
| Unknown                  | 17.0           | 8.7              | 15.5         | 8.7          | 30.0 | 9.1  |
| Predicted annual income  |                |                  |              |              |      |      |
| Low (<$34,000)           | 21.5           | 13.5             | 21.5         | 13.5         | 21.8 | 13.7 |
| Middle ($34,000-$67,000) | 19.6           | 11.7             | 20.2         | 12.1         | 16.0 | 9.2  |
| High ($67,000)           | 15.6           | 9.4              | 16.8         | 9.4          | 6.9  | 9.4  |
| Unknown                  | 21.7           | 8.4              | 22.0         | 8.8          | 19.0 | 4.6  |
| Insurance type           |                |                  |              |              |      |      |
| Medicare                 | 17.1           | 9.9              | 17.3         | 10.3         | 16.1 | 7.1  |
| Commercial               | 21.9           | 9.2              | 22.3         | 9.4          | 18.2 | 7.2  |
| At risk (Medicaid/ no insurance) | 22.7 | 20.7 | 23.7 | 21.2 | 18.9 | 18.7 |
| Other                    | 40.0           | -                | 50.0         | -            | 0.0  | -    |
| Fractions                |                |                  |              |              |      |      |
| 1-20                     | 11.0           | 3.6              | 10.5         | 3.5          | 14.5 | 4.8  |
| >20                      | 29.4           | 18.9             | 30.8         | 19.4         | 20.5 | 44.2 |
| Diagnosis                |                |                  |              |              |      |      |
| Breast                   | 19.5           | 6.9              | 21.1         | 6.7          | 11.3 | 7.5  |
| H&N                      | 29.5           | 22.8             | 31.3         | 24.4         | 22.6 | 15.9 |

(Continued)
treatment length >20 fractions (P < .01), and winter start (P < .01) were associated with increased major RTI risk, no variable interacted significantly with treatment era. With regards to minor interruption rates, age <65 (P < .01), treatment >20 fractions (P < .01), and winter start (P < .01) were associated with higher risk for the full cohort. However, only treatment length >20 fractions interacted significantly with treatment era.

**GIS analysis of RTI rates before and during COVID-19**

Major RTI rates before and during the pandemic were mapped by ZIP code across the metropolitan region by race and insurance status in Fig. 2A-D. Geographic distribution of elevated major RTI rates shifted from baseline during COVID-19 to a limited number of residential ZIP codes downtown and directly north and south of the central urban corridor, more concentrated than at baseline. Black race and Medicaid or no insurance status colocalized with highest RTI rates. ZIP codes experiencing increased RTI rates during COVID-19 overlapped or approximated ZIP codes with high SVI scores (Fig. 2E) and 2020 COVID-19 incidence rates (Fig. 2F), but these were not significant associations. The downtown location of our clinic is highlighted in these maps. LBR testing confirmed lack of association between the spatial distribution of RTI rates and baseline SVI across the full metro region (P = .11). Similarly, overlap between RTI and COVID-19 incidence rates also remained nonsignificant (P = .70). Some of the high RTI ZIP codes were in higher-income (eastern metro) regions or areas with fewer

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**Table 2 (Continued)**

|                      | Total                  | Pre—COVID-19 era          | COVID-19 era               |
|----------------------|------------------------|---------------------------|----------------------------|
|                      | Minor interruption (%) | Major interruption (%)    | Minor interruption (%)     | Major interruption (%)     |
|                      | (2-4 RT breaks)        | (5+ RT breaks)            | (2-4 RT breaks)           | (5+ RT breaks)             |
| Metastasis           | 11.3                   | 4.3                       | 9.8                       | 4.1                        |
| Lung                 | 22.8                   | 12.5                      | 22.2                      | 12.7                       |
| Prostate             | 24.7                   | 13.6                      | 26.8                      | 14.6                       |
| GI                   | 26.8                   | 15.6                      | 27.9                      | 15.5                       |
| GYN                  | 20.8                   | 28.4                      | 20.7                      | 28.7                       |
| Hematologic          | 12.8                   | 5.1                       | 13.8                      | 5.9                        |
| CNS                  | 19.4                   | 3.9                       | 19.8                      | 3.0                        |
| Other                | 13.6                   | 5.4                       | 14.4                      | 5.7                        |
| Unknown              | 0.0                    | -                         | 0.0                       | -                          |
| Distance to RT in miles |                       |                           |                           |
| 0-5                  | 23.9                   | 14.8                      | 24.0                      | 15.2                       |
| 5-10                 | 19.2                   | 13.4                      | 19.5                      | 13.5                       |
| 10-15                | 17.2                   | 10.7                      | 18.6                      | 11.6                       |
| 15-20                | 14.3                   | 12.5                      | 16.3                      | 11.1                       |
| 20-30                | 16.7                   | 8.16                      | 15.8                      | 9.5                        |
| 30-40                | 16.2                   | 5.13                      | 16.9                      | 5.8                        |
| >40                  | 20.6                   | 7.2                       | 20.8                      | 5.9                        |
| Unknown              | 21.8                   | 8.4                       | 22.2                      | 8.8                        |
| RT start month       |                        |                           |                           |
| Nonwinter (March—October) | 17.7               | 10.3                      | 18.5                      | 10.5                       |
| Winter (November—February) | 24.4             | 14.5                      | 24.1                      | 14.6                       |

**Abbreviations:** CNS = central nervous system; GI = gastrointestinal; GYN = gynecologic; H&N = head and neck; RT = radiation therapy.
COVID-19 infections (south-central metro). Likewise, many eastern suburban ZIP codes with higher COVID-19 infection activity did not experience increased RTI rates.

**Discussion**

The effect of COVID-19 on US health care delivery and cancer treatment has been broad and deep. To our knowledge, this is the first US institutional report of longitudinal RT delivery continuity across the first year of COVID-19. Encouragingly, RTI rates during COVID-19 did not worsen, but instead trended incrementally downward. This may have resulted from either system-level resilience or de facto selection for patients with durable access to care. Clinical risk factors varied in their predictive associations with RTI, potentially because of limited study size, measured or unmeasured changes in cohort population, or differing mix of disease type presentations during COVID-19 (Table 1).

At the cohort level, the pandemic neither exacerbated nor...

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**Table 3  Univariate and multivariate analysis of major (5+ RT breaks) interruptions for each treatment era**

|                       | Pre—COVID-19 era | COVID-19 era |
|-----------------------|------------------|--------------|
|                       | Unadjusted | Adjusted | Unadjusted | Adjusted | Unadjusted | Adjusted |
|                       | OR (95% CI) | P value | OR (95% CI) | P value | OR (95% CI) | P value |
| Age, y                |            |         |            |         |            |         |
| <65                   | Reference  | -       | Reference  | -       | Reference  | -       |
| ≥65                   | 0.55 (0.4-0.74) | <.01*  | 0.79 (0.56-1.12) | .19 | 0.56 (0.24-1.22) | .16 | 1.06 (0.39-2.80) | .91 |
| Sex                   |            |         |            |         |            |         |
| Female                | Reference  | -       | Reference  | -       | Reference  | -       |
| Male                  | 0.9 (0.68-1.19) | .46 | 0.78 (0.58-1.05) | .10 | 1.49 (0.72-3.17) | .29 | 1.79 (0.81-4.01) | .15 |
| Race                  |            |         |            |         |            |         |
| Black or African American | Reference | -       | Reference  | -       | Reference  | -       |
| White                 | 0.63 (0.47-0.84) | <.01*  | 0.81 (0.59-1.11) | .20 | 0.67 (0.29-1.44) | .32 | 0.62 (0.26-1.43) | .28 |
| Marital               |            |         |            |         |            |         |
| Married               | Reference  | -       | Reference  | -       | Reference  | -       |
| Nonmarried            | 1.53 (1.14-2.07) | <.01*  | 1.33 (0.97-1.84) | .08 | 3.23 (1.30-9.76) | .02* | 2.62 (1.02-8.10) | .06 |
| Predicted annual income |         |         |            |         |            |         |
| Low (<$34,000)        | Reference  | -       | Reference  | -       | Reference  | -       |
| Middle-high (≥$34,000) | 0.8 (0.61-1.07) | .13 | 1.13 (0.81-1.57) | .47 | 0.6 (0.28-1.25) | .17 | 0.62 (0.29-1.35) | .23 |
| Insurance type        |            |         |            |         |            |         |
| At risk (Medicaid/no insurance) | Reference | -       | Reference  | -       | Reference  | -       |
| Commercial/Medicare    | 0.39 (0.29-0.54) | <.01*  | 0.44 (0.32-0.62) | <.01* | 0.33 (0.16-0.70) | <.01* | 0.38 (0.17-0.83) | .02* |
| Fractions             |            |         |            |         |            |         |
| 1-20                  | Reference  | -       | Reference  | -       | Reference  | -       |
| >20                   | 6.22 (4.4-9.03) | <.01*  | 6.47 (4.56-9.45) | <.01* | 3.73 (1.64-9.62) | <.01* | 3.58 (1.55-9.34) | <.01* |
| RT start month        |            |         |            |         |            |         |
| Nonwinter (March-October) | Reference | -       | Reference  | -       | Reference  | -       |
| Winter (November-February) | 1.50 (1.15-1.94) | <.01*  | 1.68 (1.27-2.22) | <.01* | 1.64 (0.77-3.43) | .19 | 1.84 (0.83-4.07) | .13 |
| Distance to RT in miles |            |         |            |         |            |         |
| 0-10                  | Reference  | -       | Reference  | -       | Reference  | -       |
| >10                   | 0.61 (0.47-0.80) | <.01*  | 0.71 (0.53-0.93) | .02* | 0.57 (0.25-1.22) | .16 | 0.58 (0.25-1.31) | .21 |

**Abbreviations:** CI = confidence interval; OR = odds ratio; RT = radiation therapy.

* Significant at P < .05.
improved pre-existing RTI disparities; financial vulnerability and longer treatment schedules remained associated with major RTI on univariate and/or multivariate analysis (Table 3). Medicaid coverage remained a dominant predictor of high RTI rates in our study, and likely for RT access as well, consistent with high-level observations reported for ambulatory care in the US.32 Interestingly, associations were observed between a winter treatment start date and RTI risk. Potential mechanisms responsible for this finding include severe weather (ie, unseasonable heavy snowfall events) and emergence of a local SARS-CoV-2 alpha variant-driven surge between late November 2020 and January 2021. Only 1 case was documented as having treatment interrupted directly by active COVID-19 infection. No compulsory local transportation curfews were ever instituted, although voluntary “safer at home” advisories and enforcement of targeted temporary business closures and mandated remote schooling did take place.

Consistent with national19 and global33,34 trends, referrals to our department dropped acutely during the first months of COVID-19 (Fig. 1A). The pandemic has affected access across the full spectrum of cancer care, including screening,35,36 treatment,37 and even clinical trial openings.38 A dramatic example is illustrated by the decline in

Table 4 Univariate and multivariate analysis of minor (2-4 RT breaks) interruptions for each treatment era

|                        | Pre−COVID-19 era |                      | COVID-19 era |                      |
|------------------------|------------------|----------------------|--------------|----------------------|
|                        | Unadjusted       | Adjusted             | Unadjusted   | Adjusted             |
|                        | OR (95% CI)      | P value              | OR (95% CI)  | P value              |
| Age, y                 |                  |                      |              |                      |
| <65                    | Reference        | - -                  | Reference    | - -                  |
| ≥65                    | 0.66 (0.51-0.85) | <.01*                | 0.71 (0.54-0.91) | <.01*                |
| Sex                    |                  |                      |              |                      |
| Female                 | Reference        | - -                  | Reference    | - -                  |
| Male                   | 1.04 (0.82-1.31) | .75                  | 0.97 (0.76-1.25) | .84                  |
| Race                   |                  |                      |              |                      |
| Black or African American | Reference | - -                  | Reference    | - -                  |
| White                  | 0.85 (0.67-1.08) | .20                  | 0.99 (0.76-1.28) | .94                  |
| Marital                |                  |                      |              |                      |
| Married                | Reference        | - -                  | Reference    | - -                  |
| Nonmarried             | 1.24 (0.97-1.58) | .08                  | 1.26 (0.98-1.63) | .07                  |
| Predicted annual income|                  |                      |              |                      |
| Low (<$34,000)         | Reference        | - -                  | Reference    | - -                  |
| Middle-high (≥$34,000) | 0.90 (0.71-1.16) | .42                  | 1.00 (0.77-1.30) | .99                  |
| Insurance type         |                  |                      |              |                      |
| At risk (Medicaid/no insurance) | Reference | - -                  | Reference    | - -                  |
| Commercial/Medicare    | 0.80 (0.59-1.08) | .14                  | 0.94 (0.67-1.32) | .72                  |
| Fractions              |                  |                      |              |                      |
| ≤20                    | Reference        | - -                  | Reference    | - -                  |
| >20                    | 3.80 (2.93-4.96) | <.01*                | 4.00 (3.08-5.25) | <.01*                |
| RT start month         |                  |                      |              |                      |
| Nonwinter (March-October) | Reference | - -                  | Reference    | - -                  |
| Winter (November-February) | 1.40 (1.10-1.78) | <.01*                | 1.66 (1.29-2.14) | <.01*                |
| Distance to RT         |                  |                      |              |                      |
| 0-10                   | Reference        | - -                  | Reference    | - -                  |
| >10                    | 0.86 (0.68-1.09) | .21                  | 0.86 (0.68-1.09) | .22                  |

Abbreviations: CI = confidence interval; OR = odds ratio; RT = radiation therapy.
* Significant at P < .05.
screening mammography in the US, which fell by up to 96% in the northeast early on. With recovery from the first wave, screening rates rebounded to prepandemic levels. This was echoed in our local patient census numbers, although on-treatment numbers never recovered as robustly as national trends. This discordant finding might be specific to patients with cancer served by an urban safety-net clinic and warrants external validation. However, it could signal future widening of cancer outcome disparities in underserved urban locations. Modeling studies and meta-analyses suggest that pandemic-associated treatment delays will lead to increased cancer mortality, particularly in underserved populations. COVID-19 infection, itself, leads to more frequent transmission and hospitalization in immunologically compromised cancer populations, especially in Black patients.

We observed very modest interaction between treatment timing and RTI risk factors, limited to treatment length >20 fractions and minor RTI risk. Nonetheless, GIS mapping provided important complementary insight beyond our stable cohort-level findings, detecting discrete neighborhood-level shifts of racially defined RTI disparities (Fig. 2A-D). RTI burden in Black patients with Medicaid or no insurance became more geographically concentrated in the urban core, with only a handful of ZIP codes experiencing increased RTI rates during the pandemic. ZIP codes experiencing increases in RTI approximated but did not overlap significantly with elevated SVI measures (Fig. 2E) or COVID-19 incidence rates (Fig. 2F) across the full metro region by quantitative spatial analysis. Our finding that only a limited number of ZIP codes were affected by increased RTI rates has instructed us to view risk-directed high-resolution mapping of baseline and pandemic-related factors.
relevant to RTI in these most affected neighborhoods as a priority for future work.

Our central urban location positioned us to oversample from populations of patients with cancer living in racial minority, financially distressed neighborhoods. Although this may serve to improve study power to detect pandemic effect on medically underserved patients, it also limits relevance to better-resourced communities with different case mixes. Other important limitations of our analysis include the following: (1) patient selection bias and limited cohort size because of the pandemic, confining analysis to patients with the resources to make it to our clinic and start treatment; (2) potential geographic fluctuations in our catchment area toward or away from central urban areas during the pandemic because of varying system or patient-level hardships; (3) inherent difficulty distinguishing respective effect
of neighborhood-level social demographics (ie, median expected household income) versus individual patient-level factors on RTI rates\(^4\) (we could only investigate patient-level social vulnerability indirectly via a proxy, ie, Medicaid coverage); (4) biases and sensitivity constraints of our mapping of community-level COVID-19 transmission (because of potential undersampling by our local testing registry, which does not include inpatient or commercial pharmacy outpatient testing) and socioeconomic vulnerability, which was quantified according to publicly available SVI data; and (5) limitations of our retrospective data collection, which precluded analysis of detailed stage distribution, interevent timing of RTI (sequential vs separated days of interruption), exact mechanistic causes for individual RTI events, and potential attrition to other treatment centers/alternative forms of disease management. The analysis of RTI rates in patients who initiated therapy at our center required an assumption that the characteristics of our COVID-19–era referral population did not change dramatically from baseline, which is suggested but not formally confirmed by findings in Table 1.

The COVID-19 pandemic has increased hardship in underserved populations facing pre-existing cancer outcome disparities.\(^4\) The US Centers for Disease Control and Prevention and others have reported disproportionate COVID-19 transmission and mortality rates in Black and Latino populations,\(^4,47\) which have shouldered greater economic and social distress.\(^4\) Additional data and broader regional context will be required to disentangle the multifactorial effect of the pandemic and downstream public health responses on medical, financial, logistical, and social resources relevant to cancer care access. Although not directly addressed by this report, we anticipate that retrospective identification of ZIP codes with increased RTI could guide prospective confirmation and intervention strategies to mitigate obstacles to care access intensified by the crisis. Follow-up studies could include in-depth canvasing and direct outreach to these communities, supplemented by validation of individual-level predictive data to identify highest-risk patients. Use of demographic, social, and financial factors in this way may allow for automated risk-based triage of patients toward supportive resources, financial counseling, and cancer care navigation well beyond the end of the public health emergency.

For patients able to access cancer treatment, care quality has been handicapped by delayed surgeries, reduced in-person visits, and foregone adjuvant treatment.\(^34,37,49,56\) Fortunately, radiation oncology providers have rapidly re-established capacity through remote virtual care and in-clinic safety protocols.\(^19,51\) The pandemic has intensified interest\(^52\) and use\(^33\) of hypofractionated RT, such as for breast\(^53,54\) or prostate\(^55\) cancer, which may reduce burden and increase treatment value for patients well beyond the pandemic.\(^56\) Satisfaction may even increase for specific patient subgroups with expanded use of teleoncology via improved access and convenience.\(^77\) However, it remains important to consider that rural, older, and lower socioeconomic groups more frequently have substandard access to high-speed Internet or mobile technologies.\(^57,58\) Regardless of age or setting, reduced in-person health maintenance and cancer screening may result in decreased patient engagement, more advanced cancer presentations, and worsened outcome.\(^59\) Hands-on interaction, which has been so challenged by COVID-19, continues to be foundational to treatment access and quality, particularly in marginalized populations affected by trust deficits, disengagement, interrupted care, and inferior outcomes.

**Conclusions**

We provide the first US institutional report of RT treatment volume and interruption patterns during the first year of COVID-19. A persistent 36% overall decline in treated patient volume was observed across the first pandemic year. Although RTI rates trended incrementally downward, financially disadvantaged populations undergoing longer planned courses of RT remained more susceptible to major RTI during the pandemic. Formal GIS analysis added important insight, revealing discrete geographic shifts in interruption risk to marginalized racial minority patients living in urban downtown neighborhoods. Such findings could be leveraged to design focused RT access enhancement strategies tailored to specific community locations well beyond the pandemic, but this will require replication to validate and broaden relevance.

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