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Accessibility
The Tell-Tale Heart: Population-Based Surveillance Reveals an Association of Rofecoxib and Celecoxib with Myocardial Infarction

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Background. COX-2 selective inhibitors are associated with myocardial infarction (MI). We sought to determine whether population health monitoring would have revealed the effect of COX-2 inhibitors on population-level patterns of MI.

Methodology/Principal Findings. We conducted a retrospective study of inpatients at two Boston hospitals, from January 1997 to March 2006. There was a population-level rise in the rate of MI that reached 52.0 MI-related hospitalizations per 100,000 (a two standard deviation exceedence) in January of 2000, eight months after the introduction of rofecoxib and one year after celecoxib. The exceedence vanished within one month of the withdrawal of rofecoxib. Trends in inpatient stay due to MI were tightly coupled to the rise and fall of prescriptions of COX-2 inhibitors, with an 18.5% increase in inpatient stays for MI when both rofecoxib and celecoxib were on the market (P < 0.001). For every million prescriptions of rofecoxib and celecoxib, there was a 0.5% increase in MI (95%CI 0.1 to 0.9) explaining 50.3% of the deviance in yearly variation of MI-related hospitalizations. There was a negative association between mean age at MI and volume of prescriptions for celecoxib and rofecoxib (Spearman correlation, −0.67, P < 0.05).

Conclusions/Significance. The strong relationship between prescribing and outcome time series supports a population-level impact of COX-2 inhibitors on MI incidence. Further, mean age at MI appears to have been lowered by use of these medications. Use of a population monitoring approach as an adjunct to pharmacoepidemiology methods might have helped confirm the suspected association, providing earlier support for the market withdrawal of rofecoxib.

INTRODUCTION

In the United States, almost a million people are hospitalized, and 200,000–300,000 die each year of myocardial infarction (MI).[1,2] Rates of MI have increased over the last century and are attributable to lifestyle risk factors, including smoking, obesity, exercise and diet.[3,4,5] While non-cardiovascular target drugs such as fenfluramine, dexfenfluramine, terfanadine and cisapride have been shown to be risk factors for cardiovascular events,[6,7,8], their effects are rare and are not considered as contributors to long term trends in morbidity and mortality.

Nonsteroidal anti-inflammatory drugs (NSAIDs) are increasingly implicated in cardiovascular morbidity[9] and Cyclooxygenase-2 (COX-2) selective inhibitors, a class of NSAIDs, have been, in particular, associated with increased risk of MI.[9,10,11,12,13,14,15,16] Rofecoxib was withdrawn from the market after a randomized placebo-controlled trial revealed increased cardiovascular risk in patients with colorectal polyps.[17] Though similarly associated with cardiovascular risk[9], celecoxib is still prescribed widely. Many studies have supported an increased individual risk of MI, but the population-level impact of COX-2 selective inhibitor prescription has not been described or quantified despite their substantial market penetration and delayed market withdrawal.

In this study, we elucidate long-term temporal trends in rates of inpatient visits for MI to an integrated health system in Boston, Massachusetts and their correspondence with prescriptions for rofecoxib and celecoxib. We estimate the magnitude of this effect on macro-level trends in hospitalizations for MI.

METHODS

Study Setting and Population

The patient population was from Partners Healthcare System, a large multi-specialty group practice that provides care to members of a New England–based health maintenance organization. This non-profit, integrated health system includes Brigham and Women’s Hospital and Massachusetts General Hospital. The source of clinical data—patient demographic information, dates, medication, and diagnosis information, and discharge summary—

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Competing Interests: The authors have declared that no competing interests exist.

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ries—was the Research Patient Data Registry (RPDR), a central-
ized data warehouse. Institutional Review Board (IRB) approval
was obtained.

The study outcome was serious coronary heart disease, defined
as acute MI requiring hospitalization. Subjects were all patients
hospitalized for MI assigned by primary or admitting diagnosis
International Classification of Diseases, Ninth Revision (ICD-9)
code 410, from January 1 1997 to March 31 2006. This diagnostic
code has been validated by others and used as an indicator of
acute MI. [10,18,19] In our own chart review, we found that 87%
of patients assigned the code had strong confirmatory evidence of
acute MI. To calculate incidence, we estimated the denominator
by combining US Census population estimates for Massachusetts
from 1997–2005 with market share estimates for the two study
hospitals. Market share was calculated using data from the
Massachusetts Division of Health Care Finance and Policy (1999–
2004) which contains hospitalizations at all Massachusetts
hospitals. Mean yearly market share was estimated at 12.4%
(SD, 0.6%). To adjust for biases stemming from shifts in healthcare
utilization patterns and changes in health coverage and market
share, we also included total number of hospitalizations per unit
time as a covariate in our analyses.

Interrupted Time Series Analysis
Using a population monitoring framework, we tested for a change
in the population rate of MI after introduction of rofecoxib and
celecoxib using three time series analysis methods. The first was
a cumulative sum (CUSUM), regularly used in industrial process
control. More recently it has been applied to the early detection of
disease outbreaks [20] and to adverse drug events.[21,22] The
CUSUM, a type of control chart, detects sudden changes in the
mean value of a quantity of interest and provides estimates of the
timing and magnitude of change.[23] Specifically, the analysis
calculates the cumulative sum of deviations from a set value in
successive samples. An alarm threshold value is defined a priori
taking into account an acceptable false alarm rate or average run
length. Here, we used CUSUM to define whether and when a
detectable rise in cardiovascular events could have been
identified by simply monitoring the time series of monthly rate
of inpatient stays for MI.

Second, we investigated the association of the market
availability of celecoxib (January 1999–present), and rofecoxib
(May 1999–September 2004) on the time series of the monthly
rate of inpatient stays for MI using generalized linear modeling.
We assumed a Poisson distribution for modeling counts of
independent MI events. The model included binary indicator
variables for rofecoxib and celecoxib (on or off the market), and
used estimated population covered as the offset. Seasonal trends in
MIs were adjusted for by including eleven months of the year as
indicator variables. We included monthly number of total
inpatient stays to adjust for potential secular trends in healthcare
utilization. A linear trend term was included to account for long-
term changes in MI-related hospitalizations. To account for
overdispersion in the count data, extra-Poisson variability was
modeled and incorporated into estimates of standard errors.[24]

Parameter estimates were transformed to rate ratios.

Finally, we matched fluctuations in yearly incidence of
hospitalizations due to MI to prescription data on rofecoxib and
celecoxib. Total numbers of prescriptions dispensed were obtained
from the freely available IMS Health annual report on Commonly
Requested Therapeutic Class and Product Information.[25] We
measured the impact of celecoxib and rofecoxib prescription rates
by fitting Poisson regression models as described above. In this
case, we modeled yearly counts of MIs, including total underlying
population as an offset, and overall number of yearly inpatient
stays as a model covariate. A linear trend term was included to
account for long-term secular trends.[26] Prescription counts for
celecoxib and rofecoxib were examined separately and in
combination. In addition to incidence, we also examined the
association between yearly changes in the mean patient age at time
of MI with prescription volume for rofecoxib. All analyses were
carried out using the SAS statistical software (version 9.0, SAS
Institute Inc., Cary, NC).

Anchor Diagnoses
To confirm that our results were not simply reflective of systematic
bias related to referral patterns and secular trends in acuity mix at
the two hospitals, we monitored yearly changes in three anchor
diagnoses. We investigated whether yearly incidence of hospitaliza-
tions due to abdominal aortic aneurysm (ICD-9 codes 441.3–
441.4), appendicitis (ICD-9 codes 441.3–441.4), and pneumonia
and influenza (ICD-9 codes 480–487) were coincident with MIs by
two-tailed Spearman rank correlation.

RESULTS
Study Population
We identified 25,486 unique patients who had sold,603 MI-related
hospitalizations during the study period. Monthly incidence of
hospitalizations due to MI ranged from 33.3 per 100,000 inpatient
stays in March of 2006 to 56.4 per 100,000 in December, 2002
(mean, 46.2; 95 percent confidence interval, 45.1 to 47.2).
Incidence of hospitalizations due to MI ranged from 48.8 per
10,000 in 1997 and 2005 to 62.3 per 10,000 in 2001.

Interrupted Time Series Analysis
Based on the mean and standard deviation of MI incidence for
a baseline period of 1997–1998, we first tested for cumulating
deviations above a target mean of 47.1 MI-related hospitalizations
per 100,000 and a standard deviation of 2.8 per 100,000. (Figure 1)
The threshold for CUSUM was calculated as 1.18, yielding an
average-run-length of 50. In other words, we set the false alarm
rate to once per 50 months. An aberration of two standard
deviations from baseline was initially detected in January of 2000,
with a CUSUM value of 1.37 and 51.5 MI-related hospitalizations
per 100,000 stays (9.3 percent above expected). This significant
rise was eight months after the market introduction of rofecoxib
and one year after the introduction of celecoxib. A second and
sustained rise began November of 2000 with a CUSUM value of
2.08 and 54.2 MI-related hospitalizations per 100,000 (16 percent
above expected). The exceedance peaked in March of 2003,
46 months after the introduction of rofecoxib with a CUSUM
value of 16.5. Threshold was exceeded for 48 consecutive months,
ending in October 2004, one month after the market withdrawal
of rofecoxib.

Second, we modeled the impact of market availability of
celecoxib and rofecoxib on inpatient stays for MIs. For celecoxib,
inpatient stays due to MI were 41.6 per 100,000 prior to the
December 1999 release (n = 24 months; 95 percent confidence
interval, 40.4 to 42.8), and 47.4 from January 1999 to March 2006
(n = 87 months; 95 percent confidence interval, 46.5 to 48.6). MI-
related hospitalizations were 41.7 per 100,000 over the period
prior to rofecoxib introduction and post-withdrawal
(n = 47 months; 95 percent confidence interval, 40.7 to 42.7).
While rofecoxib was on the market, the rate of MI-related
hospitalizations was 49.4 per 100,000 (n = 64 months; 95 percent
confidence interval, 48.3 to 50.5), an 18.5 percent increase. We
measured the effect of celecoxib and rofecoxib dispensing on the
time series of MI-related hospitalizations by Poisson regression where the two drugs were included as indicator variables. The model for rofecoxib revealed a positive relationship with counts of MIs (rate ratio 1.14; 95 percent confidence interval, 1.09 to 1.19; \( P = 0.001 \)), explaining 28.7 percent of the deviance. The model for celecoxib also revealed a significant positive relationship with counts of MIs (rate ratio 1.09; 95 percent confidence interval, 1.01 to 1.18; \( P = 0.022 \)), explaining 5.2 percent of the deviance.

Finally, we measured the yearly impact of estimated celecoxib and rofecoxib use on hospitalizations due to MIs as a dose-response relationship using national prescription data (Table 1). Prescriptions for celecoxib and rofecoxib peaked in 2001 with 25.41 and 27.06 million prescriptions dispensed nationally, respectively. Incidence of MI-related hospitalizations also peaked in 2001 with 62.3 hospitalizations per 10,000 (Figure 2). Yearly counts of MIs were significantly predicted by prescriptions for rofecoxib (0.7% increase in MIs per million prescriptions; 95 percent confidence interval, 0.2% to 1.3%) and marginally for celecoxib (0.6% increase in MIs per million prescriptions, 95 percent confidence interval, \(-0.005\%\) to 1.3%). For every million prescriptions of both rofecoxib and celecoxib, we found a 0.5 percent increase in MI (95 percent confidence interval, 0.1 to 0.9), explaining approximately 50.3 percent of the deviance in yearly variation of MI-related hospitalizations.

We also find a significant negative association between mean patient age and prescriptions for celecoxib and rofecoxib (Spearman correlation, \(-0.67\); \( P = 0.05 \)). Over the years when rofecoxib was not available, the mean age was 66.5 compared to a mean age of 65.4 over the period of market availability. Figure 3 shows the nadir in age corresponding to the peak of rofecoxib and celecoxib prescriptions.

**Anchor Diagnoses**

To demonstrate that our findings were not simply based on changing healthcare utilization, we investigated temporal trends for hospitalizations for three other diagnoses. Though showing a positive linear increase, abdominal aortic aneurysm (Spearman correlation, 0.17; \( P = 0.66 \)), appendicitis (Spearman correlation, 0.11; \( P = 0.78 \)), and pneumonia and influenza (Spearman correlation, 0.071; \( P = 0.86 \)) were not associated with trends in MI. Further, only trends in inpatient visits for MI were significantly correlated with national prescription rates for rofecoxib and celecoxib (Spearman correlation 0.93; \( P < 0.001 \)).

**DISCUSSION**

Our findings demonstrate striking longitudinal trends in the population rate of MI and strongly suggest a population-level impact of rofecoxib and celecoxib on MI. Temporal trends in inpatient stays due to MIs are tightly coupled to the rise and fall of prescription of COX-2 inhibitors, with an 18.5 percent increase in inpatient stays for MI during the time when rofecoxib was on the market. These results are consistent with prior reports demonstrating cardiovascular effects of rofecoxib and celecoxib. [9,10,11,12,13,14,15,17,27] Further, mean age at MI appears to have been lowered by use of these medications.

Using population surveillance methods [28,29,30] we confirm a sharp rise in adverse cardiovascular events within eight months.
of the market introduction of rofecoxib and one year after launching of celecoxib. A second rise in November 2000 occurred during the same month as the publication of the Vioxx Gastrointestinal Outcomes Research (VIGOR) study.[31,32] The exceedence vanished within one month of the withdrawal of rofecoxib. The population-level findings, though based on aggregated data, are used to confirm a hypothesis based on clinical trial data [16] and to estimate the magnitude of the effect across the population.

We used two approaches to identify the impact of the prescriptions for COX-2 selective inhibitors. The first was to simply treat each drug as a binary (present or absent) variable. We find increases in inpatient stays for MI after the introduction of rofecoxib and celecoxib. Second, we applied a correlational approach to identify a dose-response relationship by modeling the temporal fluctuations in inpatient stay for MIs with national prescription rates. We find that adverse cardiovascular events coincide best with the time period of population exposure to rofecoxib and celecoxib. The analyses described are subject to the known pitfalls of ecological studies, with caveats about inferring causality.[33,34] However, our results are especially convincing given the return to baseline following the market withdrawal of rofecoxib and our confirmatory analysis. Further, this ecological finding is confirming a prior suspected association.

Our study does have limitations. Our results, based only on an inpatient population, may underestimate population-level rates of rofecoxib and celecoxib. Second, we applied a correlational approach to identify a dose-response relationship by modeling the temporal fluctuations in inpatient stay for MIs with national prescription rates. We find that adverse cardiovascular events coincide best with the time period of population exposure to rofecoxib and celecoxib. The analyses described are subject to the known pitfalls of ecological studies, with caveats about inferring causality.[33,34] However, our results are especially convincing given the return to baseline following the market withdrawal of rofecoxib and our confirmatory analysis. Further, this ecological finding is confirming a prior suspected association.

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Table 1. Yearly incidence in hospitalizations due to myocardial infarctions and corresponding national estimates of prescriptions for rofecoxib and celecoxib.

<table>
<thead>
<tr>
<th>Year</th>
<th>Myocardial infarction-related hospitalizations*</th>
<th>Total inpatient†</th>
<th>Incidence of Myocardial infarction-related hospitalizations (per 10000§)</th>
<th>Rofecoxib scripts dispensed (millions)¶</th>
<th>Celecoxib scripts dispensed (millions)¶</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>3475</td>
<td>89638</td>
<td>48.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1998</td>
<td>3654</td>
<td>93562</td>
<td>51.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1999</td>
<td>3958</td>
<td>99047</td>
<td>55.0</td>
<td>4.84</td>
<td>17.54</td>
</tr>
<tr>
<td>2000</td>
<td>4357</td>
<td>105426</td>
<td>58.8</td>
<td>20.63</td>
<td>24.91</td>
</tr>
<tr>
<td>2001</td>
<td>4644</td>
<td>105603</td>
<td>62.3</td>
<td>25.41</td>
<td>27.06</td>
</tr>
<tr>
<td>2002</td>
<td>4627</td>
<td>107898</td>
<td>61.9</td>
<td>22.04</td>
<td>26.01</td>
</tr>
<tr>
<td>2003</td>
<td>4569</td>
<td>110735</td>
<td>61.1</td>
<td>19.83</td>
<td>23.65</td>
</tr>
<tr>
<td>2004</td>
<td>3923</td>
<td>110677</td>
<td>52.6</td>
<td>13.87</td>
<td>23.92</td>
</tr>
<tr>
<td>2005</td>
<td>3641</td>
<td>111751</td>
<td>48.8</td>
<td>0</td>
<td>14.27</td>
</tr>
</tbody>
</table>

*Unique patients hospitalized for a myocardial infarction, having been assigned a primary or admitting diagnosis of myocardial infarction (International Classification of Diseases, Ninth Revision (ICD-9) code 410).
†Unique patients hospitalized at the Brigham and Women’s Hospital and Massachusetts General Hospital
§Total numbers of prescriptions dispensed were obtained from the freely available IMS Health annual report on Commonly Requested Therapeutic Class and Product Information. Estimates are derived from a national prescription sales database.
¶Incidence is calculated using the estimated underlying population market share coverage by both study hospitals

Figure 2. Association between yearly prescriptions for rofecoxib and celecoxib and incidence of myocardial infarctions. A) Scatter plot reveals the positive relationship between national prescriptions estimates for rofecoxib and celecoxib and hospitalizations due to myocardial infarction. Prescriptions for rofecoxib and celecoxib peaked in 2001 with 52,466,000. Incidence of stays due to myocardial infarction also peaked in 2001 with 62.3 hospitalizations per 10,000. B) Line graphs show the interrupted time series of myocardial infarction-related hospitalizations. Prescriptions for rofecoxib and celecoxib explained approximately 50.3 percent of the deviance in yearly variation of myocardial infarction related hospitalizations. doi:10.1371/journal.pone.0000840.g002
MI. In our analysis, we treated individual patients as independent observations, narrowing confidence intervals for our rate ratio estimates. However, these error calculations do not account for the clustering of responses associated with temporal variation in risk. The IMS prescription data were based on national estimates and may not accurately represent possible local variation in Boston. For instance, geographic variation in prescription practices for rofecoxib and celecoxib may have been disproportionately affected by media attention regarding early reports of associated adverse cardiovascular events. However, our use of yearly estimates should smooth this potential bias. The prescription estimates also do not account for continued use of the drug after its withdrawal from the market.

While part of the power of this approach stems from availability of the full interrupted time series, including the period after market withdrawal of rofecoxib, our findings highlight the importance of understanding, modeling, and surveying for baseline adverse outcomes to detect population-level aberrations from that baseline. This study was performed with data from only two hospitals in a single health care system, in a single city. In an active post launch surveillance system, such signals will need to be rapidly evaluated and adjudicated with replication in other data sets, in other regions, and through multi-signal integration approaches.

High profile failures to detect safety problems during the pre-approval period have brought new intense scrutiny on the drug approval process.[35,36,37,38,39] Revelation of an association between rofecoxib and MI [32,35,40,41] was a signal event highlighting catastrophic failures in monitoring the safety of therapeutics already on the market.[42] Because adverse effects of drugs and therapeutics are often not detected in Phase III clinical trials, [43] or they are suspected but not confirmed, a robust drug safety system requires ongoing monitoring of adverse events throughout the drug development lifecycle.[44] However, at present, safety efforts are not balanced across the lifecycle.

There is no generally accepted process or gold standard set of methods for identifying safety problems with drugs during the post launch phase. A major vehicle for hypothesis generation is the FDA’s Adverse Event Reporting System (AERS) which collects voluntary reports[45] that are somewhat limited by poor quality, under-reporting, and skewed and inadequate ascertainment.[46,47,48,49] Nonetheless, AERS-based findings are often the only basis for regulatory action.[49,50,51] Ultimately, however, it impossible to correct for inherent data limitations.

Notably, in the earlier part of the decade, it would have been very unlikely that a clinician would associate a MI with rofecoxib and hence to report it to the AERS system. Likewise, a clinician would have been unlikely to report a hip fracture in a patient taking a proton pump inhibitor.[52] There is an emerging consensus that semi-automated analysis of healthcare databases is the next logical step.[21,22] Robust post-marketing surveillance requires a multimodality approach to monitoring the health of individuals using drugs and devices. As confirmatory evidence for the veracity of a suspected association, use of a population monitoring approach as an adjunct to pharmacovigilence methods might have helped provide earlier support for the market withdrawal of rofecoxib. Without a known prior association, population health monitoring could help generate hypotheses about candidate medication risk factors. This is especially important for widely prescribed medications where there is a substantial risk of population-level effects. If used prospectively, however, to look across drugs at patterns of prescribing and outcomes, careful attention would need to be paid to issues of specificity and multiple testing.

Figure 3. Association between yearly prescriptions for rofecoxib and celecoxib and mean age of patients hospitalized for myocardial infarctions. Line graph showing a significant negative association between mean patient age and national prescription volume for rofecoxib and celecoxib (Spearman correlation, 0.67, P<0.05). Prescriptions for rofecoxib and celecoxib peaked in 2001 with 27,060,000 prescriptions dispensed nationally while mean age was 64.6, the lowest in nine years.

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Author Contributions
Conceived and designed the experiments: IK JB KM. Performed the experiments: JB MS. Analyzed the data: JB MS. Wrote the paper: IK JB KM MS.

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