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# An Instrumental Variables Approach to Estimating the Effects of Changes in the Heroin Market on Overdose in the US*

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## Abstract

We investigate a major supply shock to the US heroin market in the 1990s, the introduction of Colombian-sourced heroin, that led to a substantial rise in heroin overdose admissions. The instrumental variables approach uses the interaction of the timing of the supply shock with city-level pre-shock characteristics that have been shown to facilitate or hinder the introduction of new heroin sources. The estimation strategy allows us to disentangle the causal effects of multiple city-level heroin market factors that are correlated with overdose: the price per pure gram of heroin, the coefficient of variation of purity of heroin, and the proportion of heroin of Colombian origin. We find that changes in the price per pure gram and country of origin have substantial effects on heroin overdose admissions. The results have important implications for understanding the effects of changing heroin market conditions on the current US heroin epidemic.

JEL Classification: D49; I12

Keywords: heroin price; heroin purity; heroin overdose; instrumental variables

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# 1 Introduction

Since the 1990s, there has been a concerning reversal in the downward trend in mortality and morbidity rates in the United States (Case and Deaton, 2015). A significant factor in this reversal is the "triple wave" epidemic of deaths from prescription opioids, heroin, and illicitly manufactured synthetic opioids such as fentanyl (Ciccarone, 2017). While the complex etiology of this epidemic is still being evaluated, we focus on the economic forces that propelled a prior heroin epidemic before the widespread adulteration of heroin with synthetic opioids. We investigate a supply shock in the heroin market during the 1990s that led to a substantial increase in heroin overdoses. By investigating the causal effects of changes in the heroin market on overdose, we hope to shed light on the extent to which market forces have caused the current heroin epidemic. From a policy perspective, understanding the consequences of changes in the heroin market on health outcomes can lead to improved response times to impending epidemics. It can also help us understand the efficacy of policies that intervene in the supply or demand side of illicit drug markets.

Due to data limitations our analysis is restricted to the years 1993 through 2008. There was a substantial change to the US heroin market over this time period that has not yet been comprehensively analyzed. Opium started to be produced in substantial quantities in Colombia in the early 1990s, which was then refined into heroin, and the vast majority was trafficked to the US. This new source of supply quickly displaced heroin from Southwest and Southeast Asia (which along with Mexico were the predominant sources for heroin in the US) while the Mexican-sourced heroin supply remained (Ciccarone, Unick and Kraus, 2009). By the early 2000s almost all US heroin came from opium grown in Mexico and Colombia (Rosenblum, Unick and Ciccarone, 2014). In the later 2000s, Colombian opium production fell, while Mexican opium production began to rise. We use the timing of these events interacted with city-level characteristics that may have facilitated or hindered the effects of a new heroin source as instruments for city-level heroin market characteristics to estimate their causal effects on the incidence of heroin overdose hospital admissions.

Several studies have tried to measure the elasticities of illicit drug use and drug price (see Grossman, Chaloupka and Shim (2002) for an overview). Outside of small-scale studies (Bretteville-Jensen and Biorn, 2004; Jofre-Bonet and Petry, 2008), it is difficult to measure the effect of changes in the illicit drug market on actual use using self-reported surveys. For example, Grossman and Chaloupka (1998) use the Monitoring the Future Survey to estimate the elasticity of demand for cocaine. The survey asks high school seniors about their drug use, and may be representative of this sample, but there is no reliable survey on the number of illicit drug users or their intensity of drug use for the general population. To address this issue, scholars have investigated the effects of changes in illicit drug markets on outcomes that are not reliant on self-reporting such as drug-related emergency room visits or the numbers of arrestees who test positive for drugs (e.g. Model (1993) for marijuana, Caulkins (2001) and Dave (2006) for cocaine and heroin). We follow along these lines by estimating price elasticities with respect to the number of heroin-related overdose admissions in US hospitals. The substantive innovation of our method is to include additional market factors that are typically not controlled for and using instrumental variables estimation to reduce bias from endogeniety or omitted variables that may be present in prior estimates of illicit drug elasticities.

We estimate the effects of changes in three heroin market conditions on heroin overdose admissions in US hospitals: 1. the price per pure gram (PPG) of heroin, 2. the coefficient of variation (COV) of heroin purity, and 3. the percent of heroin observations that originate in Colombia. All of these factors have been identified in the literature as having a possible impact on heroin overdose.

A higher PPG should reduce the demand for heroin, causing either intensity of use to drop or the population of new heroin users to decline. Estimating price elasticities with respect to illicit drug use or its consequences has been an important research goal in the economics of illicit drug markets. However, other market factors may be just as important, if not more important, than price. Illicit drug markets have massive asymmetric information problems, with drug purchasers and even sellers not knowing the actual content of the substance being sold. It is even more complicated, as having zero information on heroin quality (i.e. purity) would conceivably lead to a lemons market for heroin, driving down purity, which could feasibly protect heroin users from overdose. Full information could lead to high purity heroin, but also less risk as users would not unexpectedly inject high purity heroin.

Mars et al. (2015) find evidence of distinct information differences in the heroin markets of San Francisco and Philadelphia. Philadelphia has high purity heroin and heroin is sold in open markets with visible brands and information sharing among consumers, i.e. information is good. This contrasts with San Francisco, which has low purity heroin, where the market is closed, and there are no brands or substantial information sharing among users, i.e. information is poor. Whereas in Philadelphia it is easy for even new heroin users to find high-quality heroin, in San Francisco it may take years of developing relationships with specific dealers to find a stable supply of high-quality heroin. The COV of heroin purity within a location and time is one way to measure these information problems, with a higher COV indicating less information and presumably greater risk for users.[1] It is possible that a fall in price coincides with an increase in the COV of heroin purity, and disentangling these two effects has to our knowledge not been attempted.

Reuter and Caulkins (2004) finds that there are large coefficients of variation in heroin and cocaine in the US and hypothesize that it could be a contributor to adverse consequences for users. A correlation between variation in purity and overdose has been found, for example, by Darke et al. (1999) in Australia. However, researchers have not found strong evidence of it being a major cause of overdose (Darke, 2014). The lack of strong evidence about the effects of changes in the COV of heroin purity is an additional reason to include it for consideration as a contributing factor for heroin overdose.

In addition to the COV of heroin purity, prior research has found a strong relationship in the US between heroin overdose and Colombian-sourced heroin even controlling for PPG (Unick et al., 2014). The mechanism is not well understood. Colombian-sourced heroin is similar in form to Asian-sourced heroin, generally called “white powder” heroin, although the

[1] Note that using COV as a proxy for information problems helps to deal with the aforementioned lemons market problem. A market with no information and only low quality heroin would have a small COV as would a market with lots of information. So a high COV can be thought of as a measure of the uncertainty buyers have about the quality of heroin.

actual color varies. This is in contrast to black tar heroin typically produced in Mexico. Given the proximity to the US or the desire to undercut rival suppliers as a way to obtain market share, Colombian-sourced heroin may be of particularly high purity. Alternatively, it may be more easily adulterated with harmful substances, have more variation in purity, or facilitate an open market structure that reduces information problems (Mars et al., 2015). In addition, transmission of HIV for intravenous drug users is more common in areas with white powder heroin compared to black powder heroin (Ciccarone, 2009), and HIV is itself a risk factor for overdose (Green et al., 2012).

Price, uncertainty, and source-country are inter-related parts of the retail heroin market that may or may not be contributing to the current heroin epidemic in the US and until now have not been studied together or within a causal, instrumental variables framework. We find that changes in the PPG of heroin as well as the source country have substantial effects on heroin overdose admissions and are able to explain almost two-thirds of the rise in heroin overdose admissions over the 1990s. The instrumental variables estimates show much larger effects of these heroin market conditions than OLS estimates would suggest. The estimates are robust to several different specifications.

# 2 Data

We use several sources of data for our analysis. The Drug Enforcement Agency's (DEA) System to Retrieve Information from Drug Evidence (STRIDE) database has extensive information at the city and town level on the price, amount, and purity (determined by lab tests) of heroin.[2] STRIDE includes the Domestic Monitor Program and Heroin Signature Program, which also test for a drug's country of origin. STRIDE contains many observations from arrests and seizures. However, we only use observations with a recorded price to estimate the price per

[2]Our data from STRIDE is unvalidated DEA data in the sense that DEA responses to external data requests include all releasable records requested, without regard to analytic value. DEA analyses, by contrast, may exclude selected records, as closer inspection of such records may reveal errors, inaccuracies, or otherwise unverifiable data. External analyses of DEA data, accordingly, may not always yield conclusions consistent with DEA's own findings. Any errors in analyzing the raw STRIDE data are the responsibility of the authors.

pure gram (PPG) and only use observations with a country of origin to estimate source country competition within a location. We have access to STRIDE data from 1990 through 2008, which includes 100,123 observations. We use the data cleaning and multi-level modeling technique described in Arkes et al. (2004) to estimate the heroin price, purity, and expected PPG of heroin.[3] The first level of the model estimates (expected) purity controlling for time, location, and amount. The second level of the model estimates price controlling for the expected purity from the first level. The estimated expected PPG is, thus, a measure of how much it costs for a unit of heroin given the expected purity in the local market.[4]

We use heroin overdose data from the Nationwide Inpatient Survey (NIS). In the analysis, we focus on the years 1993 to 2008 due to data limitations from STRIDE and the NIS before 1993. The NIS is a stratified national random sample of United States community hospitals. Each year of the NIS randomly takes 20% of hospitals from each stratum, so any individual hospital is generally re-sampled only a few times over the 1993 to 2008 time period. Cases of heroin overdose admission were coded using ICD-9 codes included in the billing records: primary diagnoses code of 965.01 or E code of E850.0. Each observation is the number of heroin overdose diagnoses in a particular hospital in a particular year. When the NIS is combined with STRIDE there are 16 MSAs with sufficient data to analyze.[5] Demographic and economic controls are from the March Current Population Survey (CPS) and Surveillance, Epidemiology and End Results (SEER) data sets.

The descriptive statistics in Table 1 show the wide range in heroin market price, purity, COV of purity, market concentration, and source country across US cities and over time. Table 2 shows that about two-thirds of the hospitals in the sample have some heroin overdose admissions, with the average number being about 3 per year. For comparison, there are more

[3] We make the same data restrictions as in Rosenblum, Unick and Ciccarone (2014): For consistency, only observations of heroin hydrochloride and heroin base, which are not easily distinguished by users and make up more than 80 percent of observations, are used for the analysis. However, the results are robust to including the "salt undetermined" observations in the price and purity estimates. In addition, we focus on retail purchases, those with amounts between 0.1 and 1 gram.

[4] If instead we estimated price per pure gram directly, this would hugely inflate the price of low purity observations with an infinite price per pure gram for observations with no measurable trace of heroin.

[5] These are: Baltimore, Boston, Chicago, Denver, Los Angeles, Miami, New York, Newark, Orlando, Philadelphia, Phoenix, San Diego, San Francisco, Seattle, St. Louis, and Washington, D.C.

non-heroin opioid overdose admissions on average (i.e. from prescription opioids). However, the number of heroin overdose admissions that ended in death are almost the same as that for non-heroin opioid overdose deaths indicating either the greater risk of heroin use or the greater health risks that heroin users have relative to those who abuse prescription opioids.

Table 1: Descriptive Statistics (City Level), Mean Values

| | Mean | Min | Max |
|---|---|---|---|
| PPG | 694 | 203 | 2846 |
| | (409) | | |
| Heroin Purity | 0.38 | 0.08 | 0.74 |
| | (0.18) | | |
| Coef. of Var. of Purity | 0.50 | 0.12 | 1.64 |
| | (0.25) | | |
| Market Conc. | 0.81 | 0.33 | 1 |
| | (0.20) | | |
| % Colombian | 0.43 | 0 | 1 |
| | (0.41) | | |
| Observations | 240 | | |

Notes: Standard deviation in parantheses. Data from STRIDE, 1993 to 2008. PPG in constant 2008 dollars. Market concentration is the Herfindahl Index of heroin sources.

Figure 1 shows some of the geographic variation in heroin overdose and heroin market characteristics. The trends for the Northeast and Southeast appear similar, with overdose admissions rising over the 1990s and then falling. These trends closely follow changes in the PPG, which fell over those regions in the 1990s and then rose in the 2000s. The amount of heroin coming from Colombia was similar as well, rising over the period, and it is much higher in the Southeast and Northeast than the rest of the country. One difference between the Northeast and Southeast is that the COV of heroin is highest in the Southeast and lowest in the Northeast, with the latter being the only region with substantial changes in COV, rising over the 2000s. This difference could be a contributing factor in the slower decline in heroin overdose admissions over the 2000s in the Northeast relative to the Southeast.

The West is distinct, with heroin overdose admissions falling even with a concurrent decline in PPG. There is almost no Colombian-sourced heroin in the region and the COV of heroin is relatively low, which may have been protective factors for the West's heroin using population.

Table 2: Descriptive Statistics (Hospital Level), Mean Values

| | Mean | Min | Max |
|---|---|---|---|
| Any HOD Admissions | 0.64 | 0 | 1 |
| | (0.48) | | |
| HOD Admissions | 2.95 | 0 | 288 |
| | (7.30) | | |
| Any Non-Heroin Opiate OD Admissions | 0.82 | 0 | 1 |
| | (0.38) | | |
| Non-Heroin Opiate OD Admissions | 5.70 | 0 | 129 |
| | (7.34) | | |
| Any HOD Deaths | 0.11 | 0 | 1 |
| | (0.31) | | |
| HOD Deaths | 0.14 | 0 | 5 |
| | (0.45) | | |
| Any Non-Heroin Opiate Deaths | 0.13 | 0 | 1 |
| | (0.34) | | |
| Non-Heroin Opiate Deaths | 0.16 | 0 | 4 |
| | (0.45) | | |
| Observations | 3,019 | | |

Notes: Standard deviation in parantheses. HOD is heroin overdose and OD is overdose. Data from NIS, 1993 to 2008.

The Center had the most dramatic changes in heroin overdose admissions, tripling over the time period. PPG was substantially higher than the rest of the country in the early 1990s and ended the time period being only marginally higher than the rest of the country. The share of Colombian-sourced heroin rose substantially over the time period, and the COV of heroin rose as well. All of these market factors may have worked together to exacerbate the heroin problem in the Center. The estimates below attempt to isolate these factors to determine what is driving these changes in overdose over time.

# 3 Estimation Strategy

Equation 1 estimates the non-causal OLS relationship between heroin market factors and overdose:

$$Log(Overdose_{ijkt}+1) = \beta * \mathbf{MKT_{jt}} + \alpha_k + \gamma_t + \delta_\mathbf{j} * \mathbf{X_{jt}} + \delta_\mathbf{i} * \mathbf{X_{it}} + e_{ijkt} \quad (1)$$

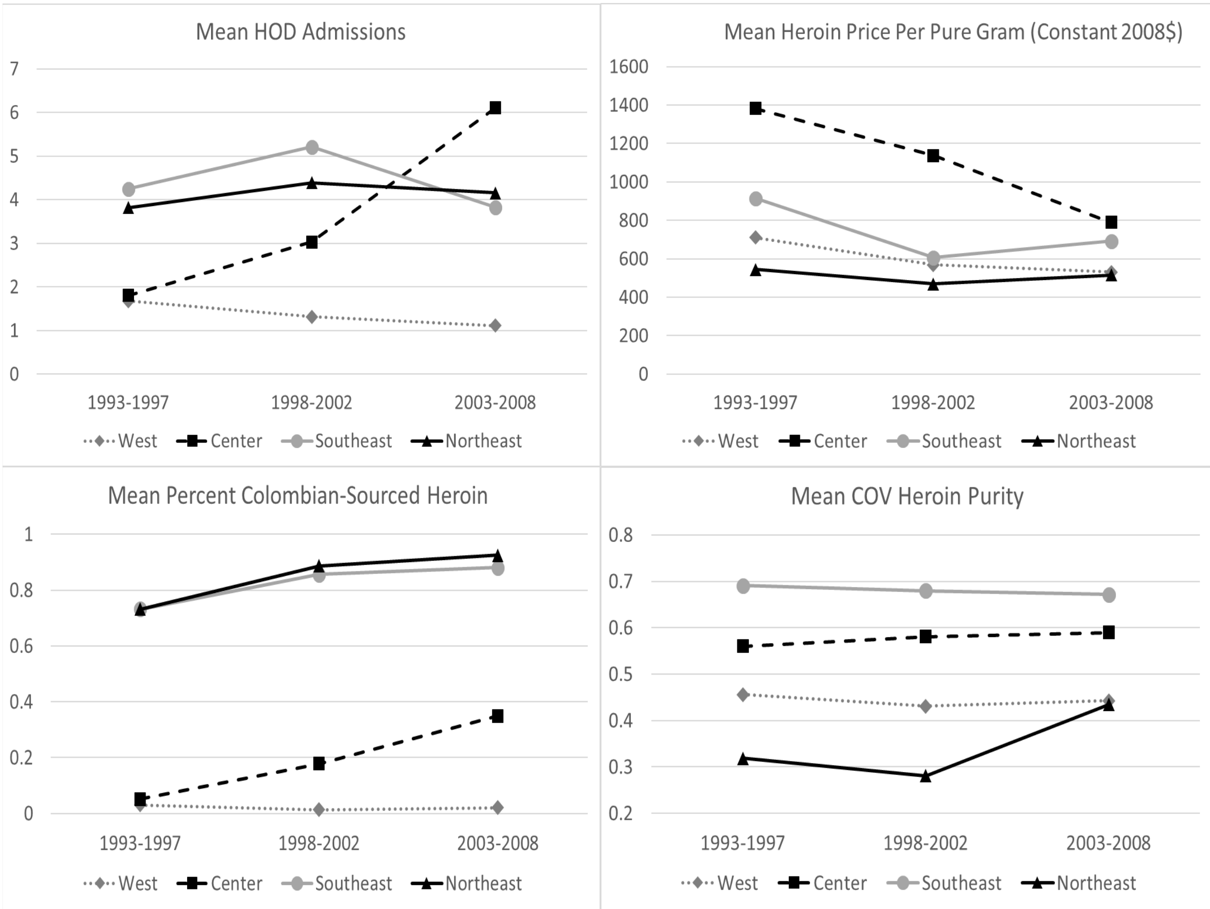


Figure 1: Regional trends in overdose and heroin market characteristics. West: Los Angeles, Phoenix, San Diego, San Francisco, Seattle. Center: Chicago, Denver, St. Louis. Southeast: Baltimore, Miami, Orlando, Washington, D.C. Northeast: Boston, New York, Newark, Philadelphia.

where $Log(Overdose_{ijkt}+1)$ is the natural log of the heroin overdose counts (plus one) in hospital $i$, city $j$, and county $k$ in year $t$. $\mathbf{MKT_{jt}}$ is a vector of heroin market characteristics: the natural log of the price per pure gram of heroin, the COV of heroin, and the fraction of heroin samples of Colombian origin. $\alpha_k$ and $\gamma_t$ are county and year fixed effects respectively. $\mathbf{X_{jt}}$ and $\mathbf{X_{it}}$ are vectors of MSA-level and hospital-level control variables respectively. $\mathbf{X_{jt}}$ includes controls for the unemployment and poverty rates, which likely have independent effects on overdose admissions (Hollingsworth, Ruhm and Simon, 2017). $e_{ijkt}$ are robust standard errors clustered at the county level.[6]

A problem with a simple OLS estimate is that the direction of causality is unclear. Low prices could be causing more overdoses via higher demand for heroin. However, an increase in overdose rates may lower the demand for heroin (through a reduction in the heroin using population from deaths, morbidity, or the increased perception of the risks of heroin), which itself would cause a reduction in price. There is recent qualitative evidence from Mars et al. (2015) that higher overdose rates may in fact raise demand by signaling "quality", making heroin more attractive to users and biasing the estimates in the other direction. A large COV of heroin purity could be causing more overdoses or high overdose rates could lower or raise demand for more consistent heroin purity. A high proportion of heroin from Colombia could be driving overdose because it is particularly dangerous or more easily adulterated with dangerous chemicals. On the other hand, cities with high overdose may be more vulnerable to competition from a new source of heroin.

A related issue is that an increasing number of overdoses could be correlated with increasing demand for unobservable reasons, such as more effective marketing from heroin sellers (Mars et al., 2015) or a rise in the price of substitutes. An instrumental variables strategy can help to reduce both this omitted variables bias and the bias from reverse causality.

[6]Counties are more consistently included over time than individual hospitals, thus county-level fixed effects and clustering are used rather than hospital-level.

## 3.1 Instrumental Variables

As discussed in Rosenblum, Unick and Ciccarone (2014), one of the most significant external changes to the US heroin market in the 1990s was the rapid and large-scale production of heroin in Colombia, coinciding with the breakup of the Medellin and then Cali cocaine cartels (Paoli, Greenfield and Reuter, 2009). Prior to the 1990s, heroin was supplied from Mexico, Southwest Asia, and Southeast Asia (Ciccarone, Unick and Kraus, 2009). Colombian-sourced heroin almost completely displaced heroin from Southwest and Southeast Asia by the early 2000s. Heroin prices in the US quickly fell during the 1990s and purity rose.

Between 1998 and 2002, President Pastrana increased drug seizures and extraditions of drug traffickers to the US. This time period coincides with the commencement of Plan Colombia (Mejía, 2015), a large influx of resources from the US to reduce the illicit drug supply. The previously rapid increase in Colombian-sourced heroin market share slowed markedly over this time period and price and purity leveled off. From 2002 to 2008, President Uribe intensified the anti-narcotic campaign of his predecessor. In 2003, two of the major drug trafficking organizations in Colombia, the AUC and the Norte del Valle Cartel, began to be broken down by the Uribe government's demobilization effort and an internal conflict respectively (Dudley, 2010). Production of opium declined in Colombia and rose in Mexico. Colombian-sourced heroin market shares leveled off and the price per pure gram declined slowly.[7]

Given the timing of the Colombian-sourced heroin expansion and the subsequent political changes that helped to rein it in, the instruments are a kinked linear time trend, with kinks in 1998 and 2002,[8] interacted with three initial city-level characteristics that have been shown to facilitate or hinder the heroin market: the market concentration of heroin source, the level of Hispanic segregation, and the distance to the Mexican border. In addition, we include the full set of interactions of these initial city-level conditions with the kinked time trends as additional

[7]This overall decline in PPG is driven by large declines in PPG in the Center of the US as shown in Figure 1, where the share of heroin sourced from Colombia continued to rise. PPG rose in the Northeast and Southeast over the 2003-2008 time period while the share of Colombian-sourced heroin changed very little.

[8]This is a similar estimation strategy to that used in Burgess and Pande (2005) to estimate the effects of a temporary bank expansion on poverty rates in rural India. It is also similar to the estimation strategy in Dobkin and Nicosia (2009), which investigates the effect of a short-term supply drop in methamphetamine on health crime and outcomes.

instruments.[9] The use of several instruments allows us to simultaneously address the possible endogeneity of the three heroin market factors of interest. This approach is particularly important, as the heroin market is not just defined by price and our estimates are the first to disentangle the effects of changes in multiple heroin market factors on overdose while addressing issues of reverse causality. We explain each of the initial city-level characteristics below.

### 3.1.1 Heroin Market Concentration

Figure 2 shows the average market concentration and average price per pure gram across the 16 cities of interest from 1993 to 2008. Concentration rose rapidly until 1997, then slowly increased with a peak in 2002. PPG went in the opposite direction, falling rapidly until 1998, rising slowly until 2001, then falling slowly afterward. There is substantial variation across the US in these changes. Mexican-sourced heroin dominated the western US over the entire time period of interest. Colombian-sourced heroin displaced Asian-sourced heroin, taking over most of the market in the eastern US. The country of origin of heroin in the center of the US shifted back and forth over the time period. PPG fell most rapidly in the center of the US where there was ultimately less market concentration than on the coasts (Rosenblum, Unick and Ciccarone, 2014).

We use the city-level initial heroin market concentration in 1993 as measured by the Herfindahl Index (i.e. the sum of squares of proportions) of heroin sources for heroin observations in STRIDE interacted with the timing of Colombian-sourced heroin expansion as one instrument for changes in the heroin market.[10] Economic intuition leads one to hypothesize that heroin markets with high initial market concentration should be more affected by the introduction of a new heroin source country than a market with more suppliers and already competitive prices.

[9] The full set of interactions are used as this strengthens the instruments considerably. The estimates are robust to removing the triple interaction terms. However, while the point estimates are similar, removing the double interactions reduces the statistical significance of the independent variables of interest and the instruments fail the overidentification test.

[10] We use the initial market concentration rather than the year by year concentration since one can argue that market concentration is itself affected by overdose rates or heroin price changes. Cities with low overdose rates or high prices may attract more competition. Alternatively, it is possible that market concentration affects overdose through unobservables unrelated to price and purity, e.g. in highly competitive markets, drug sellers might add fentanyl or other drugs to increase the strength of the drug and also increase the probability of overdose.

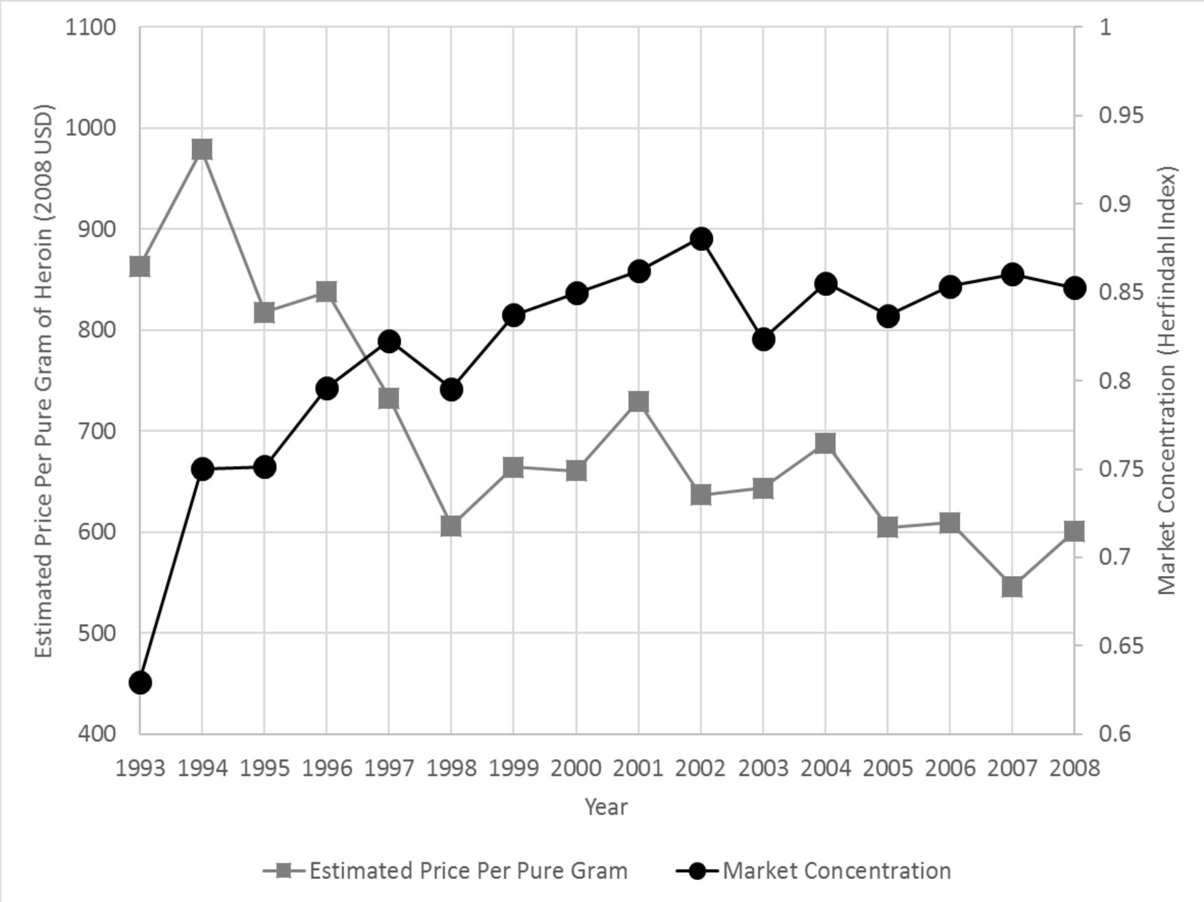


Figure 2: Average change in market concentration and estimated price per pure gram from 1993-2008. Data Source: STRIDE Database.

The subsequent change in the initially highly-concentrated market should reduce PPG and increase the proportion of Colombian-sourced heroin. The effect on the COV of heroin purity is less straightforward. If increased competition yields a more consistent product, then the COV should fall in cities with initially high market concentration. However, if high market concentration causes low COV because there are fewer products and easier information transmission, then there could be an opposite effect.

### 3.1.2 Hispanic Segregation

Rosenblum et al. (2014) find that high levels of Hispanic segregation can facilitate local heroin markets, leading to lower PPG. They discuss ethnographic evidence in Philadelphia that a highly segregated Hispanic neighborhood became the nexus for efficient heroin sales. This comparative advantage in drug dealing is likely due to social networks linking that neighborhood to Caribbean based drug traffickers, greater social cohesion and street market discipline, and the racial antagonisms of individuals and law enforcement that makes it particularly risky for white drug purchasers to be in black neighborhoods and vice versa (but not Hispanic neighborhoods). As with market concentration, we use the initial (1990 US Census) city-level dissimilarity index for our measure of segregation, then interact this with the kinked linear time trends that indicate the distinct time periods of exogneous changes to the US heroin market. After the introduction of Colombian-sourced heroin, cities with a high initial level of Hispanic segregation should have lower PPG, COV of purity, and a higher proportion of Colombian-sourced heroin. This effect is similar to that of having a high initial heroin market concentration. However, these variables are not highly correlated, so cities with both or neither of these characteristics may have had particularly large or small changes to their heroin markets. Figure 3 shows the wide variation across cities in the initial characteristics of interest.

#### 3.1.3 Distance to Mexico

Cunningham et al. (2010) finds that distance to the Mexican border has an independent effect on PPG with proximity to Mexico indicating a lower cost of transport, and, hence, lower PPG for Mexican-sourced heroin.[11] As Colombian-sourced heroin entered the US market, cities closest to Mexico, the major supply competitor, should be less affected. However, this effect should reverse over time as Colombian sources consolidate markets that were previously dominated by Asian-sourced heroin and spread west.

### 3.2 Instrumental Variables Estimation Equation

The estimation equation for the first-stage is as follows:

[11]We use the 300 mile increments that are used by Cunningham et al. (2010). However, due to a lack of observations in all distance regions, we use distance as a continuous variable rather than as a series of dummy variables.

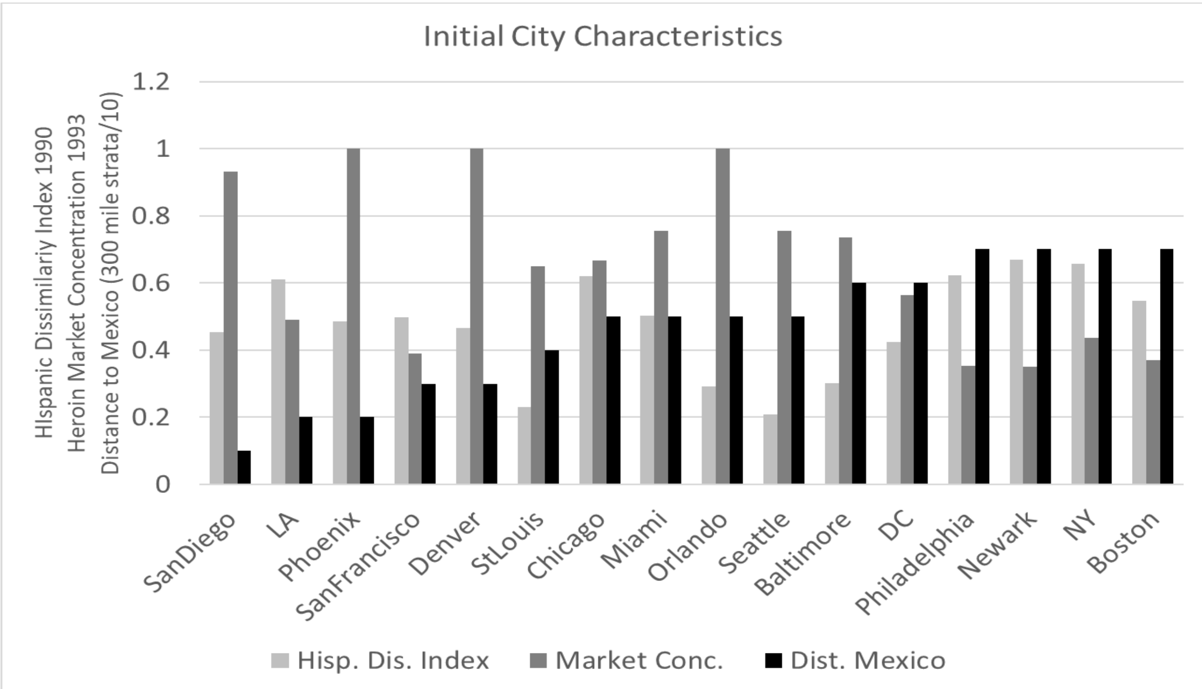


Figure 3: Note: The distance to Mexico 300-mile strata range from 1 to 7 and are divided by 10 in the graph (0.1 to 0.7) to match the scale of the other variables.

$$
\begin{aligned}
\mathbf{MKT_{jt}} = {} & \alpha_k + \gamma_t + \theta_\mathbf{1}(\mathbf{Z_j} * [t-1992]) + \\
& \theta_\mathbf{2}(\mathbf{Z_j} * [t-1997]) + \theta_\mathbf{3}(\mathbf{Z_j} * Post_{1998}) + \\
& \theta_\mathbf{4}(\mathbf{Z_j} * [t-2001]) + \theta_\mathbf{5}(\mathbf{Z_j} * Post_{2002}) + \\
& \delta_\mathbf{j} * \mathbf{X_{jt}} + \delta_\mathbf{i} * \mathbf{X_{it}} + e_{ijkt}
\end{aligned} \tag{2}
$$

where $Post_{1998}$ is 0 for 1993 to 1997 and then 1 until 2008. $Post_{2002}$ is 0 for 1993 to 2001 and then 1 until 2008. [t-1992] is a time trend that starts in 1993, [t-1997] is a time trend that starts in 1998 (and is zero before 1998), and [t-2001] is a time trend that starts in 2002 (and is zero before 2002). $\mathbf{Z_j}$ are a vector of initial city characteristics and their interactions. The initial city characteristics are the heroin market concentration in 1993[12], Hispanic dissimilarity index in 1990, and distance to Mexico. The instruments are these variables interacted with the kinked linear time trend. The second stage is Equation 1. Initial (1993) poverty and unemployment rates interacted with the kinked linear time trends are also included as controls in both stages to control for initial economic forces that may be causing differential heroin use and overdose over time (Hollingsworth, Ruhm and Simon, 2017).

The exclusion restriction for the instruments is that they only affect heroin overdose through changes in the heroin market via PPG, percent Colombian-sourced heroin, and the coefficient of variation of purity. If the timing of Colombian-sourced heroin's entry into the US market interacted with the initial city characteristics influenced other state or city-level policy changes, then the instruments would not be valid. For example, states changed their Medicaid policies in the 2000s to expand or restrict access to opioid agonist therapy (Burns et al., 2016), which could have changed heroin overdose rates. If these policy changes were influenced by the instruments, this would violate the exclusion restriction. However, it does not seem plausible that policy makers would be influenced by these factors.[13] The exclusion restriction would also be violated if the instruments affected heroin overdose through some unobservable channel. An

[12]Heroin data for Orlando only becomes reliably available in 1996, and so the 1996 concentration is used for this city. Estimation results are robust to excluding Orlando from the analysis.

[13]Using the Medicaid coverage information from Burns et al. (2016), I do not find a statistically significant relationship between initial heroin market concentration, the 1990 Hispanic dissimilarity index, or the distance from Mexico with whether a state's Medicaid program covered opioid agonist therapy in 2004.

example of this type of violation would be if heroin users differentially migrated to cities over time due to the instruments. There would be no violation if heroin users were moving because of better or worse heroin. Even if there was a plausible incentive for heroin users to move because of distance to Mexico or levels of segregation or initial market concentration, it is unlikely that this migration would align with the time-specific channel on which the instruments depend. In addition, all the estimates control for initial economic variables (initial poverty and unemployment rates) interacted with time trends and county-level fixed effects, which would control for non-time-varying unobservables. Nonetheless, a limitation of the instrumental variables strategy is that it may not be properly accounting for unobservables that may be affecting heroin use via the instruments, such as the spread of HIV or differential responses from law enforcement.[14]

# 4 First Stage Estimates

The first stage estimates are shown in Tables 3 and 4. The instruments are good predictors of the three heroin market characteristics and the standard and Sanderson-Windmeijer multivariate F-tests indicate that these are not weak instruments.[15]

The many interaction terms make the coefficients in the first-stage estimates difficult to interpret on their own. To clarify the effects of initial city characteristics on the heroin market, we compute the estimated effects of changes in the initial characteristics on the three time periods at the mean values of the initial characteristics (i.e. approximate marginal effects).[16] These are presented in Table 5. Each initial city characteristic affects the heroin market in different ways over time. Higher initial market concentration causes heroin PPG to fall rela-

[14]Looking at patterns in federal spending on illicit drug enforcement, there is a steady rise in this spending, but no sharp changes over the time period.

[15]Removing any one of the initial characteristics and its interactions, weakens the instruments (i.e. F-tests below 10) for at least one of the endogenous variables. In addition, the underidentification test (Kleibergen-Paap rk Wald F statistic), as shown in Table 6, is large, which provides additional evidence against a weak instruments problem.

[16]These marginal effects are calculated as the sum of coefficients for a given city-characteristic and its interactions for a particular time-trend where the other city-characteristic interaction terms are calculated at their mean values.

Table 3: IV-1st Stage: The Effect of Time Trends Interacted with Initial Conditions on the Heroin Market, Continued in Next Table.

| | Log(PPG) | COV | % Colombian |
|---|---|---|---|
| | (1) | (2) | (3) |
| D*H*MKT* | 1.3426* | 1.0017* | -1.4002*** |
| (1993-2008) trend | (0.7745) | (0.5692) | (0.4199) |
| D*H*MKT* | 0.0059 | 0.6940 | 0.8554 |
| (1998-2008) trend | (0.9115) | (0.9465) | (0.6539) |
| D*H*MKT* | -0.2331 | -6.0930*** | 3.2153*** |
| Post-1997 dummy | (1.1650) | (1.2665) | (0.7641) |
| D*H*MKT* | -0.5837 | -0.8165 | 0.9325** |
| (2002-2008) trend | (0.7080) | (0.8411) | (0.4160) |
| D*H*MKT* | -4.0453*** | 1.4309 | -1.0466 |
| Post-2001 dummy | (1.3364) | (1.4560) | (0.8308) |
| H*MKT* | -5.7511 | -5.5619 | 8.6767*** |
| (1993-2008) trend | (4.5048) | (3.3887) | (2.5291) |
| H*MKT* | -1.4233 | -3.3289 | -5.9059 |
| (1998-2008) trend | (5.4776) | (5.5775) | (3.8419) |
| H*MKT* | -0.2032 | 31.9147*** | -17.2074*** |
| Post-1997 dummy | (6.1887) | (7.2445) | (4.1514) |
| H*MKT* | 3.7283 | 5.2302 | -4.7032* |
| (2002-2008) trend | (4.1284) | (5.0449) | (2.3961) |
| H*MKT* | 24.8177*** | -10.4990 | 5.9927 |
| Post-2001 dummy | (7.2328) | (8.3641) | (4.5073) |
| D*MKT* | -0.8233** | -0.4085 | 0.6442*** |
| (1993-2008) trend | (0.3790) | (0.2657) | (0.2064) |
| D*MKT* | 0.3104 | -0.4585 | -0.3533 |
| (1998-2008) trend | (0.4600) | (0.4868) | (0.3299) |
| D*MKT* | -0.2914 | 2.7694*** | -1.4351*** |
| Post-1997 dummy | (0.5680) | (0.6338) | (0.3806) |
| D*MKT* | 0.1203 | 0.3790 | -0.4419** |
| (2002-2008) trend | (0.3562) | (0.4568) | (0.2103) |
| D*MKT* | 1.8744*** | -0.4915 | 0.4477 |
| Post-2001 dummy | (0.6724) | (0.7006) | (0.3939) |
| D*H* | -1.1341** | -0.5320* | 0.7193*** |
| (1993-2008) trend | (0.4417) | (0.3115) | (0.2408) |
| D*H* | 0.7877 | -0.4896 | -0.4131 |
| (1998-2008) trend | (0.5365) | (0.5467) | (0.3803) |
| D*H* | -0.5238 | 2.9834*** | -1.5371*** |
| Post-1997 dummy | (0.6357) | (0.7034) | (0.4290) |
| D*H* | 0.0421 | 0.4723 | -0.4748* |
| (2002-2008) trend | (0.4139) | (0.5158) | (0.2418) |
| D*H* | 2.4072*** | -0.4798 | 0.5806 |
| Post-2001 dummy | (0.7900) | (0.7924) | (0.4235) |

Notes: MKT is heroin market concentration in 1993. D is distance to the Mexican border. H is the Hispanic dissimilarity index from the 1990 census.

Table 4: IV-1st Stage: The Effect of Time Trends Interacted with Initial Conditions on the Heroin Market, Continued from Previous Table

| | Log(PPG) | COV | % Colombian |
|---|---|---|---|
| | (1) | (2) | (3) |
| Market Conc. 1993 * | 3.2284 | 2.6420 | -3.9562*** |
| (1993-2008) trend | (2.1836) | (1.6305) | (1.2468) |
| Market Conc. 1993 * | -0.7497 | 1.6988 | 2.6365 |
| (1998-2008) trend | (2.6520) | (2.8110) | (1.8944) |
| Market Conc. 1993 * | 2.3487 | -14.9738*** | 7.8987*** |
| Post-1997 dummy | (2.9643) | (3.6439) | (2.0657) |
| Market Conc. 1993 * | -0.8703 | -2.4755 | 2.0735* |
| (2002-2008) trend | (2.0289) | (2.6049) | (1.1819) |
| Market Conc. 1993 * | -11.1499*** | 5.0822 | -2.4816 |
| Post-2001 dummy | (3.5609) | (4.0048) | (2.1972) |
| Hisp. Diss. Index 1990* | 4.6671* | 3.3917* | -4.7028*** |
| (1993-2008) trend | (2.6604) | (2.0306) | (1.5157) |
| Hisp. Diss. Index 1990* | -2.5274 | 1.6321 | 3.2749 |
| (1998-2008) trend | (3.2766) | (3.3450) | (2.2973) |
| Hisp. Diss. Index 1990* | 3.3152 | -16.4335*** | 8.9005*** |
| Post-1997 dummy | (3.4548) | (4.1805) | (2.3841) |
| Hisp. Diss. Index 1990* | -1.0668 | -2.8799 | 2.2730 |
| (2002-2008) trend | (2.5109) | (3.0693) | (1.4450) |
| Hisp. Diss. Index 1990* | -14.9258*** | 6.1479 | -3.7418 |
| Post-2001 dummy | (4.4450) | (4.7363) | (2.5024) |
| Dist. Mex. Border * | 0.6974*** | 0.2372 | -0.3059** |
| (1993-2008) trend | (0.2229) | (0.1516) | (0.1231) |
| Dist. Mex. Border * | -0.6533** | 0.3026 | 0.1406 |
| (1998-2008) trend | (0.2797) | (0.2934) | (0.1995) |
| Dist. Mex. Border * | 0.6092* | -1.4014*** | 0.6650*** |
| Post-1997 dummy | (0.3275) | (0.3736) | (0.2256) |
| Dist. Mex. Border * | 0.1293 | -0.2222 | 0.2200* |
| (2002-2008) trend | (0.2148) | (0.2930) | (0.1281) |
| Dist. Mex. Border * | -1.0657** | 0.1496 | -0.2404 |
| Post-2001 dummy | (0.4157) | (0.3984) | (0.2088) |
| R-Squared | 0.91 | 0.70 | 0.97 |
| Observations | 3019 | 3019 | 3019 |
| F-Test | 40.87 | 26.08 | 109.78 |
| S-W F-Test | 43.81 | 24.89 | 137.38 |

Notes: Robust standard errors, clustered at county level (83 clusters), are reported in parentheses. Dependent variable: log(heroin overdose counts + 1). Controls: poverty rate, unemployment rate, demographics (% white males, %black males, % Hispanic males, % in 5-year age groups, e.g. 20-24, 25-29, etc.), log population size, log number of non-heroin hospital admissions, year dummies, and county dummies. Initial unemployment rate and poverty rate are also included as controls interacted with the kinked linear time trend. S-W F-Test is the Sanderson-Windmeijer multivariate F test of excluded instruments from the IV estimate and includes all three endogenous variables, which helps to determine whether any of one of these variables is weakly identified.

(* p<0.1, ** p<0.05, *** p<0.01)

tively rapidly for the first two time periods, but then this slows considerably after 2002. The initial level of Hispanic segregation substantially reduces PPG in the 1998-2001 time period, but this reverses for 2002-2008. Distance to Mexico has similar (if opposite) effects. Cities far from Mexico have higher prices in 1998-2001, then this slows considerably for 2002-2008. All of this aligns with the previous literature on the introduction of Colombian-sourced heroin. Price fell particularly fast in cities where competition rose the most, which are cities with a high initial level of market concentration. Hispanic segregation can facilitate the market for cheaper, purer Colombian-sourced heroin, which was particularly true as Colombian-sourced heroin was increasing its market share. Being farther from Mexico is related to higher prices, but this relationship weakens after Colombian-sourced heroin took a large share of the market.

Table 5: IV-1st Stage: The Estimated Marginal Effects of Initial City Characteristics Interacted with Market Time Trends at Mean Values.

| | 1993-2008 | 1998-2008 | 2002-2008 |
|---|---|---|---|
| | | Log(PPG) | |
| Market Conc. 1993 | -2.003 | -1.857 | 2.395 |
| Hisp. Diss. Index 1990 | -0.876 | -3.157 | 2.120 |
| Dist. Mex. Border | 0.083 | 0.451 | -0.292 |
| | | COV of Purity | |
| Market Conc. 1993 | -3.174 | -1.902 | 3.161 |
| Hisp. Diss. Index 1990 | -2.320 | -2.036 | 2.737 |
| Dist. Mex. Border | 0.407 | 0.066 | -0.256 |
| | | Percent Colombian | |
| Market Conc. 1993 | 5.409 | -3.775 | -2.918 |
| Hisp. Diss. Index 1990 | 3.951 | -2.986 | -2.691 |
| Dist. Mex. Border | -1.009 | 0.313 | 0.322 |

Notes: Mean initial market concentration is 0.574, mean Hispanic Dissimilarity Index in 1990 is 0.528, and mean distance to Mexico is 4.5 (300 mile increments).

The effects on the COV of heroin purity are similar to the effects on PPG, with higher initial market concentration and Hispanic segregation causing falls in COV over time, that slow after 2001. Cities farther from Mexico initially had a relatively increasing COV until 2001, then slowing after 2001.

Colombian-sourced heroin expanded more quickly in cities with high initial market concentration and Hispanic segregation, but this slows and then essentially stops for most of the country after 2001 and the estimates match this timing. Cities far from Mexico had less Colombian-sourced heroin relative to other cities in the 1993-2000 time period, but this slows considerably after 1998 and then even more after 2001. This fits with the geography of Colombian-sourced heroin trafficking that would have started in the southeast US via Caribbean trafficking routes or across the Mexican border and then spread from there. In summary, the instruments are good predictors of heroin market variables and their statistical relationship matches the timing of the introduction of Colombian-sourced heroin in the ways we would expect.

# 5 Second Stage Estimates

The main estimates are presented in Table 6. Perhaps surprisingly, there is no statistically significant effect of PPG on overdose admissions in the OLS estimates. In the IV estimates the effect of changes in PPG on overdose are larger than the OLS estimates and statistically significant at the 1 percent level.[17] Combining the three market factors in the estimate in column 8, we see that price and country of origin have substantial effects on overdose and that the COV of purity does not. These estimates are in contrast to the OLS estimates in column 7, where only the percent of Colombian-sourced heroin appears to matter. The estimates pass the standard IV tests for underidentification (Kleibergen-Paap rk LM statistic), rejecting the null of the estimates not being identified, and overidentification (Hansen J statistic), failing to reject that the instruments are coherent. As already mentioned, the estimates do not appear to suffer from weak identification which would otherwise falsely inflate the size of the estimated coefficients.

We can use the results to calculate the extent to which changes in the heroin market caused a rise in heroin overdose admissions. These calculations will also help to put the estimates in context and provide a rough test of the reasonableness of the findings. Between 1993 and 2002, heroin overdose admissions rose about 50 percent. Average PPG fell about 26 percent, which we estimate to have caused a 9 percent increase in overdose admissions. The fraction

[17]The OLS coefficient in column 1 for PPG is close to the estimated price elasticity for heroin with respect to emergency room admissions found by Dave (2006).

Table 6: IV-2nd Stage: The Effect of Heroin Market Changes on Heroin Overdose Admissions

| | OLS | IV | OLS | IV | OLS | IV | OLS | IV |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| Log(PPG) | -0.0938 | -0.4215*** | | | | | -0.0411 | -0.3605*** |
| | (0.0666) | (0.1208) | | | | | (0.0739) | (0.1185) |
| Coef. of Var. of Purity | | | -0.0163 | 0.2219 | | | 0.0154 | 0.4732 |
| | | | (0.0996) | (0.3031) | | | (0.1027) | (0.3487) |
| % Colombian | | | | | 0.4075*** | 0.8527*** | 0.3945** | 0.7380*** |
| | | | | | (0.1478) | (0.1794) | (0.1566) | (0.1869) |
| R-Squared | 0.42 | | 0.42 | | 0.42 | | 0.42 | |
| Observations | 3019 | 3019 | 3019 | 3019 | 3019 | 3019 | 3019 | 3019 |
| Overidentification Test | | 0.4884 | | 0.3503 | | 0.2029 | | 0.1518 |
| Underidentification Test | | 0.0126 | | 0.0091 | | 0.0100 | | 0.0073 |
| Weak Identification Test | | 283.824 | | 319.046 | | 647.375 | | 56.931 |

Notes: Robust standard errors, clustered at the county level (83 clusters), are reported in parentheses. Dependent variable: log(heroin overdose counts + 1). Controls: poverty rate, unemployment rate, demographics (% white males, %black males, % Hispanic males, % in 5-year age groups, e.g. 20-24, 25-29, etc.), log population size, number of non-heroin hospital admissions, year dummies, and county dummies. Initial unemployment rate and poverty rate are also included as controls interacted with the kinked linear time trend. Underidentification is the p-value of the Kleibergen-Paap rk LM statistic (null is that the estimates are underidentified). Overidentification is the p-value of the Hansen J statistic (if null is rejected, the instruments may not be valid). Weak Identification is the Kleibergen-Paap rk Wald F statistic.

(* p<0.1, ** p<0.05, *** p<0.01)

of heroin of Colombian origin rose about 31 percentage points causing a 23 percent rise in overdose admissions. Thus, changes in heroin market conditions can explain almost two-thirds of the rise in heroin overdose admissions. A fall in PPG played a large role in the rise in heroin overdoses over the 1990s, but changes in source-country had more than double the effect on overdose admissions. Interestingly, the COV of purity had no detectable effect. This finding may be due to the fact that the COV changed little over the time period. The lack of a statistically significant effect supports the finding of Darke (2014) that variation in purity has little effect on overdose.

The heterogeneity of the effects of changes in the heroin market on overdose are investigated in Tables 7 and 8. Table 7 splits the sample into overdose admissions for three age categories: under 25, 25-44, and 45 and older. PPG and source country matter for the youngest and oldest cohorts. However, only source country affects the middle age category at a statistically significant level. These findings indicate that cheaper, purer heroin may both attract new users and increase the intensity of use among older users. Prior research has shown that it is not the young, inexperienced user that is at more risk of overdose. Rather the 25-44 age category is the group for which overdose is most common (Darke, 2014). Thus, perhaps it is not surprising that changes in PPG would have less of an effect on this group of more experienced long-term users, whose demand for heroin may be more inelastic. Source country has a larger effect on this middle group compared to the younger and older samples (although not statistically different). From a policy perspective, it is important to know that not all demographic groups react in the same way. Observing a fall in price could alert policy makers to substantial increases in overdose among the youngest and oldest users, while changes in the physical type of heroin may have the strongest effect on 25-44 year-olds.

Table 8 divides the sample into male and female heroin overdose admissions. Interestingly, men are far more affected by source country. In addition, women are affected substantially by the COV of purity. If female heroin buyers are less experienced (the rise in heroin use among women is a relatively new phenomenon) or are more easily taken advantage of by heroin sellers and their male partners (Lorvick et al., 2014), it could explain why the high variation in purity

Table 7: IV-2nd Stage: Heterogeneous Effects of Heroin Market Changes on Heroin Overdose Admissions, Age Groups

| | Under 25 | | 25-44 | | 45+ | |
|---|---|---|---|---|---|---|
| | OLS | IV | OLS | IV | OLS | IV |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Log(PPG) | 0.0060 | -0.2837** | 0.0246 | -0.1583 | -0.0759 | -0.2108** |
| | (0.0554) | (0.1186) | (0.0634) | (0.1056) | (0.0511) | (0.0973) |
| Coef. of Var. of Purity | 0.0001 | 0.3163 | 0.0138 | 0.3268 | 0.0065 | 0.0884 |
| | (0.0526) | (0.2429) | (0.0946) | (0.2853) | (0.0608) | (0.1213) |
| % Colombian | 0.2410** | 0.4038*** | 0.3147*** | 0.6466*** | 0.2527** | 0.4334*** |
| | (0.1092) | (0.1342) | (0.1140) | (0.1650) | (0.1087) | (0.1470) |
| R-Squared | 0.28 | | 0.36 | | 0.26 | |
| Observations | 3019 | 3019 | 3019 | 3019 | 3019 | 3019 |
| Overidentification Test | | 0.1408 | | 0.3814 | | 0.4391 |

Notes: Robust standard errors, clustered at the county level (83 clusters), are reported in parentheses. Dependent variable: log(heroin overdose counts + 1). Controls: poverty rate, unemployment rate, demographics (% white males, %black males, % Hispanic males, % in 5-year age groups, e.g. 20-24, 25-29, etc.), log population size, number of non-heroin hospital admissions, year dummies, and county dummies. Initial unemployment rate and poverty rate are also included as controls interacted with the kinked linear time trend. Overidentification test is the p-value of the Hansen J statistic (if null is rejected, the instruments may not be valid). Underindentification and weak identification test results are the same as in Table 6, column 8, for all estimates.

(* p<0.1, ** p<0.05, *** p<0.01)

puts women at particularly high risk.

Table 8: IV-2nd Stage: Heterogeneous Effects of Heroin Market Changes on Heroin Overdose Admissions, Gender

| | Female | | Male | |
|---|---|---|---|---|
| | OLS | IV | OLS | IV |
| | (1) | (2) | (3) | (4) |
| Log(PPG) | 0.0021 | -0.3299*** | -0.0433 | -0.2886** |
| | (0.0513) | (0.0924) | (0.0672) | (0.1217) |
| Coef. of Var. of Purity | 0.0682 | 0.4797*** | -0.0337 | 0.3276 |
| | (0.0511) | (0.1816) | (0.1005) | (0.3199) |
| % Colombian | 0.2935*** | 0.3879*** | 0.3394** | 0.7158*** |
| | (0.1021) | (0.1339) | (0.1503) | (0.1586) |
| R-Squared | 0.29 | | 0.39 | |
| Observations | 3019 | 3019 | 3019 | 3019 |
| Overidentification Test | | 0.1267 | | 0.1863 |

Notes: Robust standard errors, clustered at the county level (83 clusters), are reported in parentheses. Dependent variable: log(heroin overdose counts + 1). Controls: poverty rate, unemployment rate, demographics (% white males, %black males, % Hispanic males, % in 5-year age groups, e.g. 20-24, 25-29, etc.), log population size, number of non-heroin hospital admissions, year dummies, and county dummies. Initial unemployment rate and poverty rate are also included as controls interacted with the kinked linear time trend. Overidentification is the p-value of the Hansen J statistic (if null is rejected, the instruments may not be valid). Underindentification and weak identification test results are the same as in Table 6, column 8, for all estimates.

(* p<0.1, ** p<0.05, *** p<0.01)

Table 9 shows the results from alternative specifications to help determine the robustness of the main results. The first set of estimates include hospital fixed effects, rather than county fixed effects. The sample is restricted to hospitals which appear at least twice in the NIS. The estimates change little even under this more restrictive specification.

Since heroin is addictive, what happens in the past may have strong effects on the present. To address this possibility, in column 3 and 4, one-year lags of the heroin market conditions are included as controls. PPG continues to have a negative impact on overdose. With lags, contemporaneous percent Colombian heroin no longer has a statistically significant effect on overdose. However, the lags of COV of purity and percent Colombian do have substantial and statistically significant effects in this specification.

There are statistical arguments to be made against using $log(overdose + 1)$ as a way to include zeros in the estimates. Burbidge, Magee and Robb (1988) argue for using the inverse

Table 9: IV-2nd Stage: The Effect of Heroin Market Changes on Heroin Overdose Admissions, Robustness

| | Hospital FE | | Lags | | $log(HOD+\sqrt{1+HOD^2})$ | | log(Heroin Deaths+1) | |
|---|---|---|---|---|---|---|---|---|
| | OLS | IV | OLS | IV | OLS | IV | OLS | IV |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| Log(PPG) | -0.0197 | -0.4074*** | -0.1285 | -0.4431*** | -0.0491 | -0.4299*** | -0.0576* | -0.1196** |
| | (0.0748) | (0.1333) | (0.0891) | (0.1587) | (0.0925) | (0.1478) | (0.0311) | (0.0523) |
| Coef. of Var. of Purity | -0.0200 | 0.2270 | 0.0741 | 0.0441 | 0.0208 | 0.5884 | 0.0130 | 0.0498 |
| | (0.0974) | (0.2766) | (0.1045) | (0.2273) | (0.1266) | (0.4402) | (0.0294) | (0.0880) |
| % Colombian | 0.4206*** | 0.6628*** | 0.1106 | 0.2830 | 0.4703** | 0.8939*** | -0.0358 | 0.1013* |
| | (0.1450) | (0.1970) | (0.2279) | (0.4274) | (0.1950) | (0.2359) | (0.0339) | (0.0606) |
| Log(PPG)$_{t-1}$ | | | 0.0013 | 0.1339 | | | | |
| | | | (0.0802) | (0.1118) | | | | |
| Coef. of Var. of Purity$_{t-1}$ | | | 0.3167*** | 0.3441*** | | | | |
| | | | (0.0894) | (0.0973) | | | | |
| % Colombian$_{t-1}$ | | | 0.4965*** | 0.3910*** | | | | |
| | | | (0.1183) | (0.1464) | | | | |
| R-Squared | 0.76 | | 0.44 | | 0.43 | | 0.14 | |
| Observations | 2867 | 2867 | 2785 | 2785 | 3019 | 3019 | 3019 | 3019 |
| Overidentification Test | | 0.2179 | | 0.2056 | | 0.1694 | | 0.1518 |
| Underidentification Test | | 0.0133 | | 0.0264 | | 0.0073 | | 0.0073 |
| Weak Identification Test | | 32.402 | | 93.220 | | 56.931 | | 56.931 |

Notes: Robust standard errors, clustered at the county level (83 clusters), are reported in parentheses. Dependent variable for columns 1-4: log(heroin overdose counts + 1). Controls: poverty rate, unemployment rate, demographics (% white males, %black males, % Hispanic males, % in 5-year age groups, e.g. 20-24, 25-29, etc.), log population size, number of non-heroin hospital admissions, year dummies, and county dummies (except for columns 1 and 2 which include hospital fixed effects). Initial unemployment rate and poverty rate are also included as controls interacted with the kinked linear time trend.

(* $p<0.1$, ** $p<0.05$, *** $p<0.01$)

hyperbolic sine transformation as an alternative. This specification is used in columns 5 and 6, and the results are not substantially different.[18]

In columns 7 and 8, heroin overdose admission that end in death are the dependent variable rather than overdose admissions in general. We find again that the PPG and percent Colombian-sourced heroin have a statistically significant effect, although the magnitude is much less than in the main estimates. Warner-Smith et al. (2001) provide an overview of the causes of heroin overdose death, which are still not well understood. The evidence does not indicate that deaths are caused by an unexpectedly high-purity dose. It is the older users with the most experience and tolerance that generally die. There is additional evidence that immediately after prison, opioid users are particularly vulnerable to overdose and death (Merrall et al., 2010; Kinner et al., 2012). Thus, it is plausible that factors beyond changes in the heroin market are the main contributors to heroin deaths.

In addition to the estimates on heroin, in Table 10 we investigate whether changes in the heroin market had any externalities for non-heroin opioid, cocaine, or amphetamine overdose admissions. There is no apparent spillover effect on non-heroin opioids, even though these are the most direct substitute for heroin. This finding makes sense in the context of the time period when the populations abusing prescription opioids were relatively more rural and suburban compared to the mostly urban heroin using population. Only recently has there been a large shift away from prescription opioids to heroin in non-urban areas. Cocaine overdose admissions are unaffected. Interestingly, the presence of Colombian-sourced heroin appears to reduce amphetamine overdoses, perhaps providing a competitive substitute.

# 6 Discussion

This article provides the first causal estimates of changes in heroin market conditions on heroin overdose admissions. We combine information from past research on the US heroin market to devise a set of instruments that can help us get answers to a complex problem. We find

[18]The main estimates are also robust to an IV-Poisson estimate and to the exclusion of any one city from the analysis (estimates not shown).

Table 10: IV-2nd Stage: The Effect of Heroin Market Changes on Non-Heroin Overdose Admissions

| | Non-Heroin Opiates | | Cocaine | | Amphetamine | |
|---|---|---|---|---|---|---|
| | OLS | IV | OLS | IV | OLS | IV |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Log(PPG) | 0.0065 | -0.0560 | 0.0424 | -0.2393 | -0.0234 | -0.0341 |
| | (0.0709) | (0.1451) | (0.1422) | (0.2809) | (0.1410) | (0.2311) |
| Coef. of Var. of Purity | 0.0514 | 0.2174 | 0.0667 | 0.4893 | 0.1202 | 0.4483 |
| | (0.0646) | (0.1634) | (0.1344) | (0.4587) | (0.1239) | (0.3953) |
| % Colombian | 0.0123 | -0.0599 | -0.2421 | -0.2438 | -0.3766** | -0.6921** |
| | (0.0877) | (0.1750) | (0.2795) | (0.4059) | (0.1677) | (0.2962) |
| R-Squared | 0.61 | | 0.55 | | 0.66 | |
| Observations | 3019 | 3019 | 3019 | 3019 | 3019 | 3019 |
| Overidentification Test | | 0.7760 | | 0.1244 | | 0.5714 |

Notes: Robust standard errors, clustered at the county level (83 clusters), are reported in parentheses. Dependent variable: log(overdose counts + 1). Controls: poverty rate, unemployment rate, demographics (% white males, %black males, % Hispanic males, % in 5-year age groups, e.g. 20-24, 25-29, etc.), log population size, number of hospital admissions (excluding overdose admissions due to drug of interest), year dummies, and county dummies. Initial unemployment rate and poverty rate are also included as controls interacted with the kinked linear time trend. Overidentification is the p-value of the Hansen J statistic (if null is rejected, the instruments may not be valid). Underindentification and weak identification test results are approximately the same as in Table 6, column 8, for all estimates.

(* $p<0.1$, ** $p<0.05$, *** $p<0.01$)

that a fall in the heroin price per pure gram can substantially increase heroin overdoses. In addition, Colombian-sourced heroin has a significant effect on heroin overdose independent of PPG and the COV of purity. Somewhat surprisingly, the COV of heroin purity has no statistically significant effect on heroin overdose, at least for men. However, the lack of a detectable effect of COV on overdose may be due to the small changes in COV after the introduction of Colombian-sourced heroin. We should note that although we have found substantial effects of market changes on heroin overdose and death, the long-term morbidity cost from overdose and use is unknown as are the externalities of spreading blood-borne diseases such as HIV and hepatitis. Thus, the estimates do not account for the full health costs of the introduction of cheap, pure Colombian-sourced heroin in the 1990s.

Although we investigate the effects of heroin market characteristics on overdose in a comprehensive way, we should note that there are limitations of the analysis. For example, one possible omitted variable is the expansion of prescription opioids soon after the introduction of Colombian-sourced heroin (Unick et al., 2013). Starting in the 1990s, doctors began prescribing more opioids for a wider number of conditions. Before 2001, heroin and prescription opioid overdose rates were similar and rising at almost the same rate. Between 2001 and 2008, prescription opioid overdoses and deaths increased much more rapidly than heroin overdose and death. With recent restrictions on prescribing opioids in the US, former prescription opioid users have turned to heroin (Mars et al., 2014). The rising number of users is likely a significant factor in the massive increase in heroin overdoses over the last few years. It is possible that the increased supply of prescription opioids, a substitute for heroin, kept heroin prices low in the 2000s, biasing our estimates towards a larger effect of low heroin PPG on overdose. On the other hand, it is possible that increased access to substitute opioids led to fewer heroin overdoses as opioid consumers switched away from heroin, which would bias the estimates in the other direction. However, this bias is unlikely to significantly affect the estimates as the prescription opioid epidemic was substantially more concentrated in rural than urban areas over the time period of interest (Paulozzi and Xi, 2008). Indeed, our estimates find no spillover effects of changes in the heroin market on prescription opioid overdose or death in the cities in our sample. In addition, the fact that heroin is an addictive good means that a rise in price may have very different effects on overdose than a fall in price, which should caution policy makers about using our estimates to predict what would happen if PPG and source country reverted back to the heroin markets of the early 1990s.

Heroin is not a perfectly inelastic good and consumers respond to market conditions. These findings fit with previous studies showing that consumers of illicit drugs respond to price. A Drug Enforcement Administration (2016) report estimates that the already low heroin PPG fell by more than 40% between 2010 and 2014. Our estimates would predict that this fall in PPG would cause a 15% increase in overdose admissions and 5% increase in heroin overdose deaths, while in fact heroin overdose deaths more than tripled. Hence, a significant decline in PPG can only explain a small fraction of the current heroin epidemic.

In addition to price changes, the Drug Enforcement Administration (2016) report estimates a substantial shift from Colombian to Mexican-sourced heroin, with the Mexican-sourced share of the market rising from about a third in 2010 to almost 80% in 2014. Our estimates would predict that this shift away from Colombian-sourced heroin should reduce overdoses. However, the current epidemic is not a reversal of the 1990s. Colombian-sourced heroin displaced Asian-sourced heroin over the 1990s, and it is not clear what the effect should be of Colombian-sourced heroin in turn being displaced by Mexican-sourced heroin. In addition, a new high quality Mexican-sourced heroin that mimics Colombian-sourced heroin (Ciccarone, 2017), recently entered the US heroin supply along with fentanyl and other synthetic opioid contamination. These recent changes in the heroin market combined with a rising demand for heroin as a substitute for prescription opioids are a likely explanation for the recent increase in heroin overdoses.

Although this research has shown that market conditions affect overdose admissions, there remains the question of why market conditions differ so much across US cities and what can be done to change them. Heroin source and type have implications for overdose (Ciccarone, 2009; Unick et al., 2014), but through mechanisms which remain unclear (Mars et al., 2015). De-ghetto-ization and dispersing markets to reduce information sharing could create a desirable lemons problem in the heroin market if it encourages a less dangerous product. However, with the recent addition of cheap, synthetic opioids to the heroin supply, greater information asymmetries may make heroin even more deadly.

From a policy perspective, our findings have several implications. An increase in cheap and pure heroin or a change in the type of heroin in a city should serve as a warning to public health officials. Rees et al. (2017) find that access to naloxone (which reverses opioid overdoses) and Good Samaritan Laws (protecting those who help people overdosing from criminal prosecution) can reduce the incidence of overdose. There are other policies that would reduce overdose rates such as improved access to substance abuse treatment and supervised injecting sites. Even if it is very difficult to change the supply side of the heroin market directly (Reuter and Kleiman, 1986), understanding the heroin market itself, how its characteristics change over time and vary across locations, can help to determine where to efficiently send resources to combat overdoses before incidence starts to rise.

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