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Expired carbon monoxide levels in self-reported smokers and nonsmokers in prison

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Breath carbon monoxide (CO) is a convenient, widely used method for abstinence validation, with cutoffs of 8–10 ppm commonly employed. The goal of the present study was to determine an appropriate CO cutoff to differentiate nonsmokers and smokers within a large sample (N=374) of female prisoners incarcerated at a correctional facility in Virginia. Mean age of the population was 34.5 years, 49.2% were White, and 29% had less than a high school education. Smoking prevalence was 74.1% within the prison population. Examination of CO levels versus smoking self-report using a receiver operator characteristic (ROC) analysis revealed that a CO cutoff of 3 ppm resulted in the best sensitivity (98.1%) and specificity (95.8%). Overall ROC area under the curve was 99% (95% CI=98.2%–99.9%). This same cutoff was optimal for smoking subgroups including Black and light (<10 cigarettes/day) smokers. Results suggest that CO cutoffs higher than 3 ppm may misclassify some smokers as nonsmokers and underestimate the prevalence of smoking.

Introduction

Measuring abstinence from smoking is necessary to determine the effectiveness of smoking cessation clinical trials and tobacco control programs and to understand the relationship between smoking and health outcomes (Hughes et al., 2003). Self-report of smoking status appears to be reliable among participants in population surveys (Vartiainen, Seppala, Lillsunde, & Puska, 2002), where it may not be feasible to obtain biological verification because of the large number of participants involved in the survey or survey methodology (e.g., telephone, Internet, or mailed surveys). However, self-report of abstinence may be unreliable, particularly with adolescents (Caraballo, Giovino, & Pechacek, 2004; Dolcini, Adler, Lee, & Bauman, 2003), pregnant women (Russell, Crawford, & Woodby, 2004; Velicer, Prochaska, Rossi, & Snow, 1992), medically ill patients (Schofield & Hill, 1999; Velicer et al., 1992), and individuals participating in clinical trials for smoking cessation (Patrick et al., 1994). In circumstances where self-report may be unreliable, biological verification of smoking status has become standard practice. Exposure to tobacco smoke can be ascertained through several biological markers, including nicotine or cotinine concentrations in plasma, saliva, and urine and carbon monoxide (CO) in blood or expired air (see Benowitz et al., 2002, for a review of these methods). Measuring CO in expired breath samples is noninvasive and inexpensive, provides immediate feedback, and is a reliable and valid measure of recent smoking (Benowitz et al., 2002). Cutoff values of 8–10 parts per million (ppm) of CO have generally been used to discriminate current smokers from nonsmokers (Jarvis, Tunstall-Pedoe, Feyerabend, Vesey, & Saloojee, 1987; Morabia, Bernstein, Curtin, & Berode, 2001).

Some researchers have questioned the appropriateness of these cutoff values for CO and have suggested that values of 3–6 ppm may provide a more sensitive and specific indicator of current smoking (Jarvors, Hatch, & Lamb, 2005; Low, Ong, & Tan, 2004). Although biochemical verification is not always necessary for all types of smoking research, determining appropriate cutoffs for smoking

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abstinence in clinical trials is important because of demand characteristics that may lead to unreliability in self-report (Benowitz et al., 2002). The combination of unreliable self-report (i.e., reporting a successful quit attempt while continuing to smoke) and an inappropriately high threshold (i.e., 8–10 ppm vs. 3–6 ppm for classifying smokers and nonsmokers) may lead to an overestimate of treatment efficacy.

The present study was undertaken to further examine the relationship between self-reported smoking and levels of expired-air CO to provide new information about optimal CO cutoff levels for distinguishing smokers from nonsmokers. Data were obtained from a population of female prisoners who were participating in a survey assessment of smoking behaviors and attitudes. Thus, the study extends previous observations in two ways. First, it focuses exclusively on female smokers from a population that represents low socioeconomic status and educational attainment. Second, it encompasses a large group of Black smokers. Research has shown that Black smokers have higher serum cotinine levels than would be expected based on the reported number of cigarettes smoked per day (Caraballo et al., 1998). Further, Black smokers are more likely to be lighter smokers (10 cigarettes/day [CPD] or less; Caraballo et al., 1998; Okuyemi, Ahluwalia, Richter, Mayo, & Resnicow, 2001). However, the relationship between CO levels and cigarettes per day has not been examined in a Black population with regard to cutoff levels for distinguishing self-reported smokers from nonsmokers and light smokers from nonsmokers.

We anticipated that self-reports of smoking would be relatively unbiased in this sample. Smoking prevalence is three times higher among female prisoners than among women in the nonincarcerated population (Cropsey, Eldridge, & Ladner, 2004), making smoking more normative and less stigmatized among prisoners. Further, survey participants were not involved in a smoking cessation program and, thus, did not have any incentive to be untruthful about their smoking status. Although biochemical verification is generally not used in large population surveys of smoking attitudes, self-report in these situations has been found to be highly reliable (Vartiainen et al., 2002). Thus the setting and population used is appropriate for performing this comparison of self-report and CO levels and for drawing conclusions about optimal cutoff levels that can distinguish self-reported smokers from nonsmokers.

Method

Participants

The 374 women surveyed were incarcerated in the largest women's prison in Virginia, with a total population of about 1,200 prisoners. Between April 2003 and May 2004, every effort was made to invite the entire female population of the prison to participate in this study. In an effort that moved sequentially through the 15 housing units, informal announcements were made and informational flyers were distributed to all potential participants, both smokers and nonsmokers. Each housing unit was approached to participate in this study only once. Women interested in participating filled out contact information on the flyer and placed it in a locked box located in each housing unit. A research staff member checked the locked box regularly and contacted each potential participant. Approximately 200 women were in segregated housing or in an acute medical or psychiatric unit and were not eligible to participate in the study, leaving approximately 1,000 eligible participants. A total of 488 women expressed interest, 388 provided written informed consent, and 374 completed the assessment battery, yielding a participation rate of approximately 38% of the eligible prisoner population.

A shorter survey of the entire female population was conducted in June 2004 to determine if the participants who completed the study were similar to the prisoner population as a whole. A total of 813 women (including women who may have completed the original survey) completed a five-question anonymous survey about their age, race/ethnicity, education level, smoking status (smoker, ex-smoker, or nonsmoker), and, if they identified themselves as a smoker, typical daily smoking rate. The two survey groups were comparable on all demographic variables and smoking rate. Smokers were slightly overrepresented in the original study sample (74.1%) as compared with the larger prison population (70.2%). Because of the large sample sizes involved, these differences were statistically significant; χ^2 (2, N=1,187)=6.4, p=.04.

In this particular prison facility, smoking was not permitted in the medical, work (e.g., industry, cosmetology), educational, or other common areas within the prison. However, prisoners had relatively unrestricted time for smoking and were free to smoke in their housing units or outside. All participants were 18 years of age or older. Participation was voluntary. Study procedures were approved by the Office of Research Subjects Protection (institutional review board) at Virginia Commonwealth University, and a Certificate of Confidentiality was obtained from the National Institutes of Health to further protect the confidentiality of participants.

Procedures

Participants were called to the medical area of the prison during normal working hours (between 9 A.M.

and 5 P.M.) in groups of 10–12 and were given a copy of the informed consent form to read. The research assistant described the major aspects of the study and answered questions about the study. Participants were told that the purpose of the study was to understand the smoking characteristics of female prisoners. Potential participants were taken individually to a private room to answer remaining questions and to discuss informed consent. Prison staff was not present for the informed consent discussion but did witness signatures on the consent form.

After providing written informed consent, participants provided a carbon monoxide sample using the monitor manufacturer's standardized procedures. Participants were asked to inhale and hold their breath for 20 s and then exhale to provide a breath sample for CO analysis. Samples were tested using the Vitalograph BreathCO, which provides a reading of CO in parts per million (ppm). Readings were not corrected for ambient levels of CO; however, all breath samples were collected in the medical area of the prison, where smoking is not permitted. After the CO level was determined, the participant was given a packet containing the smoking attitudes survey, which she completed and returned to the research assistant. Because of prison regulations about payment of stipends for research participation, participants were not compensated for participating in the survey, but they were thanked for volunteering. The survey included questions about demographics, smoking behavior, substance abuse, and psychiatric history and was part of a larger study investigating the differences between smokers, nonsmokers, and ex-smokers on substance abuse and psychiatric characteristics.

Data analyses

Based on self-report, respondents were classified as smokers, ex-smokers, or never-smokers. Ex-smokers reported that they had been abstinent for 3 years on average (range=1 month to 23 years). A preliminary analysis comparing ex-smokers (n=39) and never-smokers (n=58) showed that these groups did not differ significantly on age, race, education level, marital status, or number of children.

All data analyses were performed using SPSS version 13. Receiver operator characteristic (ROC) curves were calculated to determine the optimal cutoff for carbon monoxide using self-report as the reference. A ROC curve is constructed by plotting the true-positive rate (sensitivity) against the false-positive rate (1–specificity) of an instrument to determine the optimal cutoff of a particular test, when compared with a gold standard instrument. A sensitive test is one that is positive in the presence of the target condition. A specific test is one that is negative in the absence of the target condition. The point on the curve where the combined values of sensitivity and specificity are highest is considered the optimal cutoff.

The area under the ROC curve was calculated separately for the following groups: Smokers (n=277) and nonsmokers (n=97); Black smokers (n=136) and nonsmokers (n=54); White smokers (n=141) and nonsmokers (n=43); and light smokers (n=47), defined as smoking fewer than 10 CPD (as used by Okuyemi et al., 2001) with more than 60 min since the last cigarette, and nonsmokers (n=97). The area under the curve (AUC) is a measure of discrimination and generally takes on values between .5 (no discrimination) and 1.0 (maximum discrimination).

Results

Smoking characteristics

The sample was evenly split with almost half (49.2%) reporting their race as White and the remainder identified as Black (42.6%) or other (8.2%). The average overall age of participants was 34.5 years (SD=9.1). About two-thirds of participants had a high school diploma, high school equivalency, or better. Most participants were divorced or had never been married, and almost all (97.9%) had children (M=3.0 children, SD=1.6).

Among participants who were current smokers (n=277, 74.1%), the average age of smoking initiation was 13.5 years (SD=4.7), and the average age at onset of regular smoking was 16.3 years (SD=4.9). Significant differences were found between White and Black smokers on age at smoking initiation and regular smoking, with Whites initiating and regularly smoking at younger ages (12.3 years and 15.3 years, respectively) relative to Black smokers (15.1 years and 17.4 years, respectively; both p values $<.001$). The mean duration of smoking was 17.3 years (SD=9.1 years), with no significant difference in length of smoking between racial groups. For participants who reported being ex-smokers, the median duration of smoking abstinence was 15.5 months (range=1–120). The median number of previous quit attempts was 2.0 (range=0–96), and the median length of time since the last quit attempt was 12.0 months (range=0–328). Black smokers reported having attempted to quit smoking more recently (8.0 months, range=0–120) compared with Whites (12.0 months, range=0–300).

For current smokers, the mean score on the Fagerström Test for Nicotine Dependence (FTND; Heatherton, Kozlowski, Frecker, & Fagerström, 1991) was 6.5 (SD=1.7), indicating high nicotine dependence. Whites smoked an average of 19.2 CPD

(SD=8.2) and reported their highest level of regular smoking was 29.1 CPD (SD=15.3). Blacks reported 11.1 CPD (SD=10.7) and highest smoking rate of 15.8 CPD (SD=13.6; both p values <.001). The mean number of cigarettes smoked the previous day was 17.1 (SD=7.9) for Whites and 10.1 (SD=6.5) for Blacks, with average length of time since the last cigarette being 44.1 min (SD=39.4) and 61.4 min (SD=59.8), respectively (both p values <.001). Black smokers were significantly more likely to be classified as light smokers (22.2%) compared with White smokers (5%; p<.001). Slightly more than half of smokers (54.6%, n=154) reported regularly smoking 11 CPD or more.

CO levels were calculated for smokers (M=15.24, range=0–41), nonsmokers (M=0.32, range=0–2), and ex-smokers (M=0.89, range=0–6). Smokers had significantly higher expired CO levels compared with ex-smokers and nonsmokers, $F(2, 363)=152.79$, $p<.0001$, with no significant differences noted between nonsmokers and ex-smokers. Two participants who reported being current smokers had a CO level of 0 ppm, three self-reported smokers had a CO level of 1 ppm, none of the self-reported smokers had a CO level of 2 ppm, and five self-reported smokers had a CO level of 3 ppm. We examined the correlation for current smokers between expired CO and time since last cigarette, and after we removed two outliers (360 and 510 min from last cigarette), this correlation was not significant ($r=-.114$, p=.07). Figure 1 shows the significant correlation for current smokers between expired CO and the number of cigarettes smoked that day (r=.38, p<.001). Figure 2 shows the correlation for current smokers between the number of cigarettes smoked the day before and CO level (r=.40, p<.001).

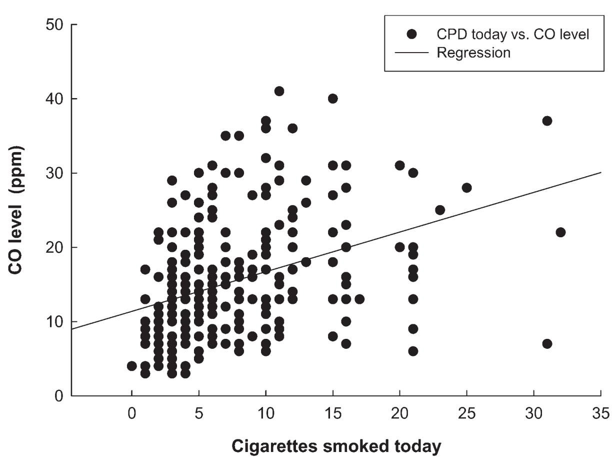

Figure 1. Correlation between the number of cigarettes smoked on the day of testing and carbon monoxide level (n=259).

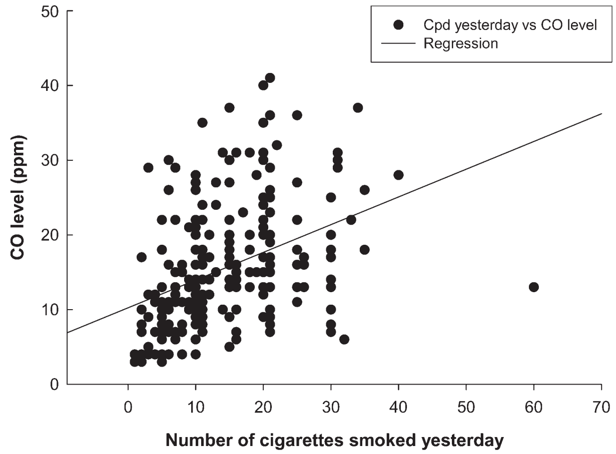

Figure 2. Correlation between the number of cigarettes smoked yesterday and carbon monoxide level (n=255).

ROC analysis comparing smokers and nonsmokers

The ROC curve for smokers and nonsmokers is displayed in Figure 3. The AUC is .99 (95% CI=.982–.999), which is almost perfect discrimination between the two groups. The optimal cutoff for indicating current smoking was 3 ppm, with a sensitivity of 98.1% and a specificity of 95.8%. Table 1 shows sensitivity and specificity values for different CO levels. Using the sensitivity and specificity of this cutoff, we found a positive predictive value of 98.5%, indicating the probability that a person is smoking when the test is positive (given a 74.1% prevalence of smoking).

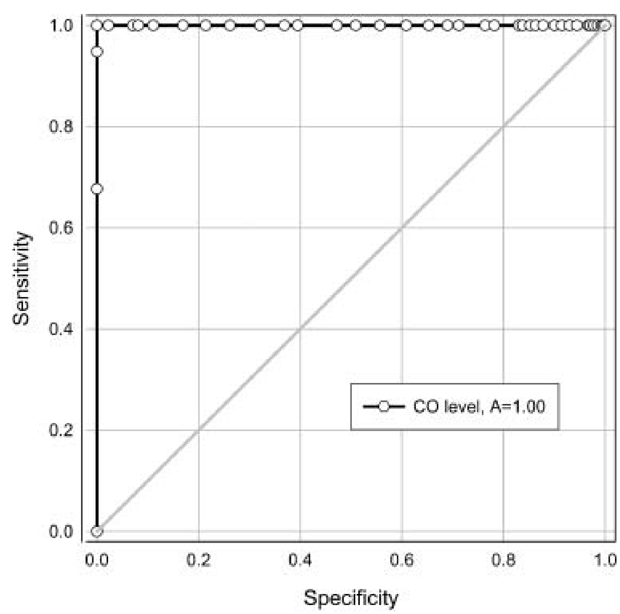

Figure 3. Receiver operating characteristics between smokers and nonsmokers (n=364).

Table 1. Sensitivity and specificity of expired carbon monoxide cutoffs.

Carbon monoxide cutoff (ppm)[a]	Sensitivity[b]	Specificity[c]	1–specificity[d]	Sensitivity+specificity[e]
0	1.000	0	1.000	1.000
1	0.993	0.663	0.337	1.656
2	0.981	0.905	0.095	1.886
3	0.981	0.958	0.042	1.939
4	0.963	0.968	0.032	1.931
5	0.918	0.979	0.021	1.897
6	0.907	0.979	0.021	1.886
7	0.885	1.000	0.000	1.885
8	0.825	1.000	0.000	1.825
9	0.781	1.000	0.000	1.781
10	0.732	1.000	0.000	1.732

Note. [a]The cutoff for expired CO level indicates that a test at or above that level would be a positive test (believed to have smoked). A test reading below that level would indicate not smoking. [b]Sensitivity is defined as the percentage of positive tests (using a cutoff value) when the participant self-reported smoking. [c]Specificity is defined as the percentage of negative tests (using a cutoff value) when the participant self-reported not smoking. [d]1–specificity is defined as the percentage of false positive tests using a cutoff value (e.g., percentage of self-reported nonsmokers classified as smokers). [e]Sensitivity+specificity was calculated to identify the optimal expired CO cutoff with the highest combined sensitivity and specificity.

ROC analysis comparing White and Black smokers and nonsmokers

Separate ROC analyses were conducted to determine the optimal CO level cutoff for smoking among different racial groups. Similar AUCs were found for distinguishing between White (AUC=.997, 95% *CI*=.992–1.00) and Black (AUC=.989, 95% *CI*=.974–1.00) smokers and nonsmokers. The optimal CO cutoff to distinguish smokers from nonsmokers remained at 3 ppm or more for both White and Black smokers. For White smokers, the 3-ppm cutoff had a sensitivity of 99.3% and a specificity of 95.3%; for Blacks, a cutoff of 3 ppm yielded a sensitivity of 99.1% and a specificity of 95.3%. The positive predictive value for this test was 98.4%.

ROC analysis comparing light smokers and nonsmokers

A separate ROC curve was calculated to determine the optimal cutoff to distinguish light smokers (<10 CPD and >1 hr since last cigarette; n=47) from nonsmokers (n=97). Our definition of light smoking as less than 10 CPD fits well with the distribution of our own data (*Mdn*=11.5 CPD) and was consistent with the definition used by Okuyemi et al. (2001) in discriminating among light, moderate, or heavy Black smokers. Using this definition of light smoking, we found the AUC for light smokers and nonsmokers to be .97 (95% *CI*=.93–1.00). The optimal CO cutoff remained at 3 ppm, with a sensitivity of 100% and a specificity of 92.9%. The positive predictive value of this test was 97.6%.

Discussion

In the present study, the optimal CO cutoff to discriminate current smokers from nonsmokers was 3 ppm or higher, with high sensitivity and specificity. In previous research, individuals with expired CO levels of up to 8–10 ppm have been categorized as nonsmokers (Jarvis et al., 1987; Morabia et al., 2001). This cutoff range has been shown to have acceptable sensitivity and specificity to differentiate current smokers from abstinent smokers or nonsmokers across different populations (Benowitz et al., 2002; Fortmann et al., 1984; Shoptaw et al., 2002). However, because demand characteristics of smoking cessation programs may encourage participants to provide false information about smoking status, some researchers have proposed a lower cutoff range of 3–6 ppm for improved sensitivity and specificity (Javors et al., 2005; Low et al., 2004).

In the present study, where participants had minimal situational demands to provide false information about smoking status, a cutoff of 3 ppm showed high sensitivity and specificity. Further, multiple separate analyses were performed to determine whether the cutoff value of 3 ppm remained consistent across racial groups and for light smokers. A cutoff value of 3 ppm remained robust with very high sensitivity, specificity, and positive predictive value for all groups examined.

The most significant contribution of this research is that it demonstrated excellent sensitivity and specificity for smoking detection via breath CO, even in a prison environment with high exposure to environmental tobacco smoke. Although we did not measure ambient CO levels in this prison, Hammond and Emmons (2005) reported high ambient levels of second-hand smoke in prison facilities, ranging from 3 to 11 $\mu g/m^3$ in the housing units and other areas of the prison that allow smoking. These levels of second-hand smoke are much higher than in the homes of smokers, where a weekly median concentration of 1 $\mu g/m^3$ has been reported (Leaderer & Hammond, 1991). However, given the low cutoff values demonstrated in the present study and the low means of CO levels among nonsmokers and ex-smokers (less than 1 ppm), it is unlikely that ambient levels of second-hand smoke influenced levels of CO in expired air. Further, given that all CO measurements were taken in the medical section of the prison, where smoking is not permitted, we do not expect that ambient CO levels influenced these readings. Overall, being able to use a relatively noninvasive method to detect smoking, such as breath CO, is an advantage, particularly with a prison population who may be reluctant to provide urine, saliva, or blood because of concern about how those samples may be used (e.g., drug screening or DNA testing).

The findings from this study suggest that use of CO cutoff values of 8–10 ppm, which are commonly used for abstinence verification, would sharply decrease sensitivity (e.g., to 73.2%–82.5%; Table 1) with only a modest increase in specificity. The use of high CO cutoffs to verify abstinence can result in a substantial number of smokers being classified as nonsmokers, providing an erroneous picture of smoking prevalence. When these higher cutoff values are used in smoking cessation studies, they may result in overestimation of abstinence success rates for cessation interventions. The present study supports findings of other researchers who have proposed a cutoff value of 3 ppm to differentiate current smokers from abstinent smokers or nonsmokers (Javors et al., 2005; Low et al., 2004). Although these studies did not use another form of biochemical verification of smoking status (e.g., cotinine), when self-report was used as the gold standard, CO levels of 3–6 ppm were found to be the most sensitive and specific.

Because this study was conducted in a population of female prisoners, representing 38% of all smokers in the prison, the findings may not generalize to males, nonprisoners, or the remainder of the in-prison smoking population. However, in other research, the range of cutoff values for exhaled CO has been comparable in males and females (Zeman, Hiraki, & Sellers, 2002), and we have no reason to expect that incarcerated males and females would differ from nonincarcerated males and females in this regard. The relatively low response rate was likely because many prisoners were unavailable to participate in this study because of work or school activities during the day. Further, we were not able to offer any compensation or incentive for participation, which likely limited the response rate. Given that these measures took about an hour to complete, and nothing could be given to compensate prisoners for this time, it is not surprising that we had only a 38% completion rate. However, we have no reason to believe that those who volunteered for the study differed in any systematic way from those who did not volunteer, as corroborated by similar demographic and smoking variables across these subgroups.

Another limitation was that participant self-report was used as the "gold standard" to determine smoking status. However, situational demands to misrepresent smoking status were likely to be minimal in this setting. Smoking is more prevalent among female prisoners than among women in the general population (Cropsey et al., 2004) and, therefore, more normative and less stigmatized. Further, the self-reported smoking rates with this sample of prisoners (74.1%) were similar to the smoking rates reported in other samples of prisoners (70%–80%; Conklin, Lincoln & Tuthill, 2000; Cropsey et al., 2004; Cropsey & Kristeller, 2005), lending credibility to these self-report data. In addition, participants had volunteered to provide a broad range of information about their smoking behavior and were not participating in a smoking cessation trial, so there were few motivators to "fake good" and provide false information about their current smoking status. Under these conditions, similar to other population surveys of smoking, self-report is likely to be more accurate and reliable. Had participants tried to "fake good" and under-reported their true smoking levels, the optimal CO cutoff value would have been far higher than observed (Javors et al., 2005). Finally, the mean CO levels recorded by nonsmokers and ex-smokers was less than 1 ppm, with only four ex-smokers and no nonsmokers recording a CO level higher than 2 ppm, lending further credence to their self-report.

The third limitation is that CO cutoff values are influenced by smoking prevalence (Cummings & Richard, 1988), and the prevalence of smoking in this population of prisoners was 74%—much higher than in comparable nonincarcerated populations. This high prevalence may have influenced the sensitivity and specificity of the CO cutoff value. However, these high rates of smoking are similar or lower than the universal rates of smoking that would be expected of individuals who are entering a smoking cessation treatment study and, thus, represent a sensitive and specific measure of current smoking.

In the present study, an exhaled breath CO level of 3 ppm or more was indicative of self-reported smoking with very high sensitivity and specificity. Using a higher CO cutoff of 8–10 ppm may misclassify some smoking individuals as abstinent and may influence the outcomes of smoking cessation treatment studies. This cutoff was the same for other subpopulations of smokers in this sample, including lighter smokers (<10 CPD) or Black smokers. We recommend an optimal CO cutoff level of 3 ppm or higher as the best indicator of smoking in situations with low demand characteristics.

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