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The Puzzle of Marijuana Use and Forced Vital Capacity

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Abstract

In study after study, marijuana use has been found to be associated with increased forced vital capacity (FVC). This is puzzling, because marijuana is commonly consumed by inhalation of its smoke, and smoke exposure of any kind is not generally considered a cause of increased FVC. Although this observation was first made decades ago, a satisfactory explanation remains elusive. In this review we survey the evidence supporting the relationship between marijuana use and increased FVC, discuss potential threats to validity when inferring causation, and, presupposing a possible causal relationship, pose two key questions. First, what are possible physiologic or pathophysiologic mechanisms by which marijuana use might increase FVC? Second, why might this effect be consistently observed with marijuana use but not with tobacco use? Explanations for the first question include lung and chest growth and remodeling from strenuous marijuana smoke inhalation and reductions in lung elastic recoil from marijuana smoke exposure. Explanations for the second include differences between marijuana and tobacco in smoke composition and patterns of consumption, such as smoking topography. Finally, the possibility that smoke, whether from marijuana or tobacco, might have nonmonotonic effects on FVC depending on the degree of exposure is explored. In synthesizing a curated breadth of epidemiologic and physiologic science, we leverage a perplexing observation to generate potential insights and avenues for further research into the biological effects of smoke, from marijuana or otherwise, on the respiratory system.

Keywords: cannabis; marijuana smoking; smoke; respiratory function tests; vital capacity

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One of the more perplexing observations regarding marijuana use is the consistent demonstration of its association with greater forced vital capacity (FVC). This is unusual because marijuana has largely been consumed via inhalation of marijuana smoke (1, 2), and generally, inhalation of smoke of any sort—such as tobacco, wood, or other biomass smoke—is not considered a cause of increased FVC (3–15). So what explains this unusual physiologic observation? In this review, we survey the evidence supporting the relationship between marijuana use and increased FVC, with attention to key studies; explore threats to validity when inferring causation; and discuss possible mechanistic hypotheses. The increasingly permissive regulatory environment for marijuana in the United States has been accompanied by an increase in the prevalence of marijuana use (16–20). Understanding the relationship

between marijuana use and lung physiology is a key piece of a scientific, medical, and public health concern that will only grow in importance over the coming years.

Evidence of Marijuana's Effect on FVC

Studies of marijuana's effect on pulmonary function date back to at least the 1970s (21–28). As early as 1973, marijuana use was observed to have an acute bronchodilatory effect, likely caused by delta-9-tetrahydrocannabinol in marijuana smoke aerosol, with a temporary, measurable increase in specific airway conductance, as well as in forced expiratory volume in 1 second (FEV_1) (22, 23, 28–30). Whether marijuana use, like tobacco use, causes a long-term decrease in FEV_1 is uncertain and continues to be investigated. Some studies have revealed an association between marijuana use and lower FEV_1 (31, 32), but most studies have not (33–41). The exact nature of the relationship between marijuana use and FEV_1 remains a topic of active investigation but is not the focus of the present review.

In contrast, studies have generally documented a relationship between marijuana use and increased FVC, as early as 1986, when Tilles and colleagues compared the FVCs of 15 female marijuana users with those of 26 tobacco users and 27 nonusers of either marijuana or tobacco (42). Multiple subsequent studies have produced similar findings, some of the most robust of which come from the CARDIA (Coronary Artery Risk Development in Young Adults) cohort and the Dunedin Multidisciplinary Health and Development Research Study (the Dunedin study) (43, 44).

In 2012, Pletcher and colleagues published an analysis of the relationship between marijuana use and lung function in the CARDIA cohort (43). The cohort is composed of men and women from Oakland, Chicago, Minneapolis, and Birmingham who were aged 18–30 years at the time of enrollment in 1985. The cohort participants were followed for 20 years, and spirometry measurements were obtained at several follow-up visits. Marijuana use was measured as lifetime exposure in joint-years, with one joint-year of exposure equivalent to 365 joints or pipe bowls; the median number of joint-years after 20 years of follow-up was 0.9 (equivalent to 329 lifetime joints or bowls) among marijuana users who never used tobacco and 1.5 joint-years (equivalent to 548 lifetime joints or bowls) among marijuana users who had also used tobacco. Whether marijuana exposure was modeled as a categorical or a continuous variable, the conclusion was the same: marijuana use was associated with increased FVC. The authors estimated that up to 7 joint-years, every joint-year of exposure was associated with a 20-ml increase in FVC.

The Dunedin study is a birth cohort of individuals born in 1972 and 1973 in Dunedin, New Zealand. The relationship between marijuana use and pulmonary function has been evaluated at several points during cohort follow-up, including at ages 21, 26, 32, and 45 years (44–47). At age 45, 242 (27%) of 881 participants reported never having used marijuana, 510 (58%) participants reported up to 5 joint-years of lifetime exposure to marijuana, and 129 (15%) participants reported more than 5 joint-years of lifetime exposure to marijuana. Hancox and colleagues (47) estimated that every joint-year of exposure was associated with a 6.6-ml increase in FVC (95% confidence interval [CI], −0.1 to 13.9 ml); when analyses were restricted to the 425 participants who had never used tobacco (232 of whom reported using marijuana), the authors estimated that every joint-year of exposure was associated with a 19.8-ml increase in FVC.

Several other studies have shown an association between marijuana use and increased FVC (Table 1; *see* the data supplement for the search strategy, a study flow diagram, and further study details). The same has been observed in NHANES (National Health and Nutrition Examination Survey) (38, 48), in SPIROMICS (Subpopulations and Intermediate Outcome Measures in COPD Study) (49), among U.S. veterans with human immunodeficiency virus infection (50), among Australians (40), among Canadians (32, 51), and among Trinidadians and Tobagonians (52). Studies demonstrating the opposite are few. An early study from 1980 of 74 marijuana users in Los Angeles compared with matched control subjects showed that marijuana users had lower FVCs than control subjects, but the difference was not significant (34). Aside from this study, however, data from different populations in different geographies and different time periods have been remarkably consistent in their finding that marijuana use appears to be associated with increased FVC.

Threats to Validity

Are these data sufficient to conclude that marijuana use causes increased FVC? As few smoke exposures are known to increase FVC, such a conclusion would naturally invite skepticism.

A principal concern with studies of marijuana use relate to the strong correlation between marijuana use and tobacco smoking (53). Tobacco smoking poses a risk for bias from confounding of any causal path between marijuana use and lung function. Investigators counter the risk for confounding by statistical adjustment of exposure to tobacco smoke as measured in cigarette pack-years or by restricting analyses to strata of participants who have or have not ever used tobacco. However, tobacco smoke is not a consistent cause of increased FVC, so the risk of observing a spurious relationship between marijuana use and increased FVC because of confounding, in the absence of a true relationship, is low.

Another concern relates to measurement bias when assessing exposure to marijuana. As nearly all studies measure exposure by self-report, there is potential concern for underreporting and misclassification. However, there is little reason to believe that underreporting of marijuana use is differential regarding FVC, and nondifferential misclassification regarding outcome will tend to bias toward the null (54). In the setting of nondifferential underreporting, the true effect of marijuana on FVC may be larger than the measured estimate of effect.

Establishing causation from observational data is an iterative process of eliminating possible threats to validity. Although uncertainty persists, the consistency of the signal prompts consideration of the mechanisms by which marijuana use might truly cause increased FVC and reasons why this effect is observed with marijuana use and not with tobacco use.

How Marijuana Use Could Increase FVC

Tashkin and Barjaktarevic proposed that marijuana use is akin to competitive swimming (55). A study by Wu and colleagues from 1988 showed that when smoking marijuana, marijuana users tended to inhale marijuana smoke deeply to achieve large inspiratory volumes and also to prolong

Table 1. Study design features and conclusions of studies that report forced vital capacity as an outcome

Study	Study Design	Study Sample	Conclusion
Tashkin *et al.*, 1980 (34)	Cross-sectional study with separate sampling of marijuana users and nonusers	Young men in Los Angeles	There was no significant difference in FVC and percentage predicted FVC between marijuana smokers and nonsmokers.
Tilles *et al.*, 1986 (42)	Cross-sectional study with separate sampling of marijuana users and nonusers	Young women in Boston	Marijuana smokers had a significantly higher percentage of predicted FVC.
Tashkin *et al.*, 1987 (97)	Cross-sectional study with separate sampling of marijuana users and nonusers	Young adults in Los Angeles	No significant difference in FVC was found in sex-stratified analyses of four groups: marijuana users who currently smoked tobacco, marijuana users who did not currently smoke tobacco, marijuana nonusers who currently smoked tobacco, and marijuana nonusers who did not currently smoke tobacco.
Tan *et al.*, 2009 (51)	Cross-sectional analysis of a population-based sample	Persons older than 40 yr in Vancouver, Canada	Marijuana smokers had a significantly higher postbronchodilator percentage of predicted FVC compared with marijuana never-smokers. The comparison was unadjusted, and marijuana smokers were younger, more likely to be male, more likely to be White, less likely to have an annual income <$25,000 (Canadian), more likely to be current tobacco smokers, and less likely to have hypertension.
Hancox *et al.*, 2010 (47)	Cross-sectional analysis of a population-based birth cohort	32-yr-old persons from Dunedin, New Zealand	Each joint-year of marijuana exposure was significantly associated with 12.0 ml greater FVC. When restricted to never tobacco smokers, the point estimate was 17.5 ml greater FVC, although the confidence interval did not exclude zero.
Pletcher *et al.*, 2012 (43)	Longitudinal analysis of a population-based cohort (CARDIA) followed for up to 20 yr	Adults from Oakland, Chicago, Minneapolis, and Birmingham	Exposure to marijuana was significantly associated with a larger FVC. The effect of marijuana exposure on increased FVC is strongest at lower degrees of exposure and attenuated at higher degrees of exposure.
Kempker *et al.*, 2015 (38)	Cross-sectional analysis of a population-based sample (NHANES 2007–2010)	Persons ages 18–59 yr in the United States	Current use of marijuana and lifetime exposure to marijuana were both associated with significantly higher percentage of predicted FVC.
Papatheodorou *et al.*, 2016 (48)	Cross-sectional analysis of a population-based sample (NHANES 2007–2012)	Persons ages 18–59 yr in the United States	Past and current use of marijuana was associated with a significantly larger FVC.
Morris *et al.*, 2018 (49)	Cross-sectional analysis of a multicenter cohort with outcome-specific sampling of persons with no COPD, mild to moderate COPD, and severe COPD	Tobacco-exposed (greater than 20 pack-years of exposure) adults in 12 locations across the United States	Marijuana use was associated with a significantly larger FVC. When cumulative lifetime marijuana exposure was analyzed as a four-level ordinal variable, the point estimates suggested a possible nonlinear relationship, but no statistical testing for nonlinearity was reported.
Tan *et al.*, 2019 (32)	Cross-sectional analysis of a population-based sample	Adults in 9 locations across Canada	Users of marijuana and users of both marijuana and tobacco had a significantly higher mean postbronchodilator percentage of predicted FVC than never users of either. The comparisons were unadjusted, and there were significant differences in BMI and education across groups.
Sakhamuri *et al.*, 2019 (52)	Cross-sectional analysis of a population-based sample	Persons older than 40 yr in Trinidad and Tobago	Marijuana use was significantly associated with 155-ml greater FVC.
Wenger *et al.*, 2021 (50)	Cross-sectional study with separate sampling of persons with and without HIV infection	U.S. veterans with and without HIV infection	Among U.S. veterans with HIV infection, marijuana exposure, whether modeled as current use or as joint-years of exposure, was significantly associated with a higher percentage of predicted FVC, but this was not found among veterans without HIV infection.

(*Continued*)

Table 1. (*Continued*)

Study	Study Design	Study Sample	Conclusion
Vozoris *et al.*, 2021 (98)	Cross-sectional analysis of a sample of symptomatic adults	Persons older than 40 yr with respiratory symptoms in the United States	Marijuana exposure was associated with a significantly larger FVC. Marijuana exposure was associated with a higher percentage of predicted FVC, but this difference was not statistically significant.
Hancox *et al.*, 2022 (44)	Longitudinal and cross-sectional analysis of a population-based birth cohort	45-yr-old persons from Dunedin, New Zealand	Each joint-year of marijuana exposure was associated with 6.6-ml greater FVC, although the confidence interval did not exclude zero. When restricted to never tobacco smokers, each joint-year of marijuana exposure was significantly associated with 19.8-ml greater FVC.
Barjaktarevic *et al.*, 2022 (39)	Cross-sectional analysis of a multicenter cohort with outcome-specific sampling of persons with no COPD, mild to moderate COPD, and severe COPD	Tobacco-exposed (greater than 20 pack-years of exposure) adults in 12 locations across the United States	The rate of FVC decline among persons who reported current marijuana use at baseline was 10 ml/yr faster than for persons who reported that they had never used marijuana, but the difference was not statistically different. Data on marijuana exposure were available only from study enrollment but not during the period of follow-up.
Najman *et al.*, 2023 (40)	Cross-sectional analysis of a birth cohort	30-yr-old persons from Brisbane, Australia	Persons who had recently used marijuana but not tobacco had a significantly higher mean percentage of predicted FVC compared with participants who had used neither marijuana or tobacco.
Barjaktarevic *et al.*, 2023 (41)	Cross-sectional analysis of a multicenter cohort with outcome-specific sampling of persons with no COPD, mild to moderate COPD, and severe COPD	Tobacco-exposed (greater than 20 pack-years of exposure) adults in 12 locations across the United States	The rate of FVC decline among persons who reported current marijuana use at enrollment was 7 ml/yr faster than for persons who reported that they had never used marijuana, but the difference was not statistically different. Data on marijuana exposure were available only from study enrollment but not during the period of follow-up.

Definition of abbreviations: BMI = body mass index; CARDIA = Coronary Artery Risk Development in Young Adults; COPD = chronic obstructive pulmonary disease; FVC = forced vital capacity; HIV = human immunodeficiency virus; NHANES = National Health and Nutrition Examination Survey.

the breath-hold time during which the marijuana smoke is retained in the respiratory tract (56). Tashkin and colleagues likened these smoking topography practices to the deep inhalations and prolonged breath-holds of competitive swimmers, some studies of whom have demonstrated larger FVC and total lung capacity than in comparator populations (57–63).

The analogy has intuitive appeal. However, the mechanism by which the training and conditioning of elite competitive swimmers might increase lung volumes is not clearly defined, and multiple hypotheses have been proposed, including enhanced ventilatory muscle strength; increased transthoracic and transpulmonary pressure from immersion in water; intermittent local hypoxia; and, perhaps, the concurrence of any or all of these stimuli—as competitive swim training often begins in childhood—during the alveolar stage of lung development (64). Whether and to what degree these proposed mechanisms can be applied in analogy to the smoking practices of marijuana users is uncertain. The intense training and conditioning of competitive swimmers constitutes an atypical mechanical strain on the respiratory system but also on the bones, musculature, and connective tissues of the thorax as well as other parts of the axial and appendicular skeleton. Mechanical strain on the respiratory tract, such as after pneumonectomy in humans and in animal models, is known to stimulate lung growth (65, 66); it is possible that repetitive inspiration to total lung capacity, as part of competitive swim training or as a way to inhale marijuana smoke, might represent a similar stimulus. However, for elite aquatic athletes, mechanical strain on the respiratory tract is paired with intense mechanical strain on the chest wall, which may be associated with the development of physically wider chests and biacromial breadth (57). No similar mechanical strain on the chest is necessarily experienced by marijuana users in the act of inhaling marijuana smoke. As such, it is unclear if competitive swim training is an appropriately analogous exposure to which to compare marijuana use. Perhaps a better comparison might by musical training for vocalists or wind instrumentalists, which also requires deep inhalations, prolonged breath holds, and controlled exhalations but does not induce comparable mechanical strain on the skeletal system. Although musical training to sing or to play wind instruments has sometimes

been associated with larger FVC (67–70), this finding has not been consistently observed (71–77).

An alternative or, perhaps, companion explanation might relate to changes in lung elastic recoil caused by marijuana smoke. Restrictive lung diseases, such as pulmonary fibrosis, increase lung elastic recoil, which has the effect of decreasing the total lung capacity and FVC. In contrast, emphysema and bullous lung disease decrease lung elastic recoil, increase lung compliance, and, in some cases, may increase total lung capacity (78, 79). However, the increase in total lung capacity is not consistently accompanied by an increase in FVC, because the loss of lung elastic recoil from tobacco smoking is a component cause of expiratory airflow obstruction, which in turn may result in airway closure and an increase in residual volume. As such, any increase in total lung capacity caused by tobacco-related loss of lung elastic recoil may not result in a parallel increase in FVC and, at late stages of disease, likely contributes to its decrease.

Still, given the paucity of exposures known to cause an increase in FVC, it may be worth considering whether marijuana use might sufficiently affect lung elastic recoil to increase total lung capacity without causing substantial airway closure and thereby also to increase FVC. Were this to be the case, one might expect that lung volume measurements would indicate an association between marijuana use and increased total lung capacity in excess of an increase in residual volume, if any, and this is indeed what has been observed. In the Dunedin study, each joint-year was associated with an 18-ml increase in total lung capacity but only a 10-ml increase in residual volume at 45 years of age (44). In a study of U.S. veterans with human immunodeficiency virus infection, Wenger and colleagues found that veterans who smoked marijuana had a greater percentage of predicted total lung capacity compared with veterans who did not, with an adjusted mean difference of 7.1%, but no significant difference in percentage of predicted residual volume (50). In a convenience sample of urban New Zealanders, Aldington and colleagues found that a history of marijuana smoking was associated with an estimated 140-ml greater total lung capacity (95% CI, −20 to 310 ml) but only 20-ml greater residual volume (95% CI, −70 to 100 ml) (37). These data suggest that some degree of airway closure may be present in people who smoked marijuana, but the resulting increase in residual volume is less than the increase in total lung capacity, potentially from decreased lung elastic recoil.

One might also expect to observe an association between marijuana use and radiographic evidence of changes to the lung parenchyma that might reasonably correlate with reduced lung elastic recoil: bullous disease, emphysema, or decreased attenuation on computed tomography images. Although case series of bullous lung disease and emphysema attributed to marijuana use are abundant (80–86), data from larger studies are mixed. In the aforementioned study of urban New Zealanders, marijuana use was associated with lower attenuation on computed tomography images; compared with nonusers, the relative area of lung at full inspiration with attenuation values less than −950 Hounsfield units for marijuana users was significantly higher by an adjusted mean difference of 2.4% (37). However, this was not observed among a sample of current and former tobacco smokers in the United States (49).

Marijuana Use versus Tobacco Use

Given the widely accepted causal relationship between smoke exposure—especially tobacco smoke exposure—and chronic airflow obstruction, much of the science on marijuana use and pulmonary function has focused on outcome measures of expiratory airflow obstruction, such as the FEV_1 and the FEV_1-to-FVC ratio. What has emerged instead from this body of literature is the repeated finding of an association between marijuana use and increased FVC. This observation poses a conundrum: why would this effect be observed with marijuana use, but not, consistently, with tobacco use? Three possible explanations are considered here.

Differences between Marijuana Smoke and Tobacco Smoke

Studies comparing the characteristics of marijuana smoke and tobacco smoke have generally observed considerable similarity in their properties but have pointed out notable differences. Key compositional differences between marijuana smoke and tobacco smoke include the presence of cannabinoid compounds (delta-9-tetrahydrocannabinol, delta-8-tetrahydrocannabinol, cannabinol, cannabidiol, cannabigerol, and cannabichromene, among others) in marijuana smoke and their absence in tobacco smoke and the presence of nicotine and tobacco-specific nitrosamines in tobacco smoke and their absence in marijuana smoke. A study of mainstream marijuana and tobacco smoke by Moir and colleagues from 2008 demonstrated qualitative similarities in smoke composition, with hydrocarbons, aromatic amines, and carbonyl compounds detected in comparable quantities in both; quantitative differences depended on experimental smoking conditions related to puff volume and interval (87). The authors hypothesized that the higher quantities of ammonia and other nitrogen-containing compounds in marijuana smoke and the higher quantities of mercury and cadmium in tobacco smoke may have been related to differences in the marijuana and tobacco growing conditions. Graves and colleagues also found considerable similarities in the chemical composition of marijuana and tobacco smoke in their analysis published in 2020, with the identification of 231 compounds in common; the authors note that aromatic and polycyclic aromatic compounds constitute a relatively greater contribution to the hydrocarbon species found in tobacco smoke, whereas mono- and sesquiterpenoid compounds constitute a greater contribution to the hydrocarbon species found in marijuana smoke (88). Graves and colleagues also observed that marijuana smoke particles are slightly larger in diameter compared with tobacco smoke particles and contain more than three times greater total mass, differences the authors suggested may be attributable to the presence of filters on the tobacco cigarettes and their absence from the marijuana joints that were tested.

How these differences in marijuana smoke and tobacco smoke might lead to potentially different effects on FVC is not readily apparent. As noted previously, smoked marijuana is known to cause modest, temporary bronchodilation (29, 30); this effect is believed to be caused by delta-9-tetrahydrocannabinol in the marijuana smoke aerosol, which exerts an anticholinergic effect mediated by presynaptic CB1 receptors (89). However, this effect does not clearly explain any long-term increase in FVC from marijuana use.

Differences in Smoking Topography

Studies comparing differences in smoking topography—the quantitative assessments of smoking behaviors—when smoking

marijuana and when smoking tobacco are few. In 1988, Wu and colleagues studied 15 habitual smokers of marijuana and tobacco; they observed differences in puff volume (78 vs. 49 ml), puff duration (4.0 vs. 2.4 s), inhaled volume (1.75 vs. 1.31 L), breath hold time (14.7 vs. 3.5 s), and number of puffs per joint or cigarette (8.5 vs. 13.5) when comparing marijuana smoking to tobacco smoking topography (56). Wu and colleagues also observed that marijuana smoking was associated with greater deposition of smoke particles in the respiratory tract and a fourfold greater increase in carboxyhemoglobin concentration, which they attributed in part to larger and deeper inhaled volumes and longer retention times.

Whether differences in smoking topography—greater puff volumes, longer breath holds, and consequently greater exposure of smoke to the alveoli relative to the conducting airways—could explain potentially different effects of marijuana smoke and tobacco smoke on FVC is uncertain. Notably, more recent data suggest that smoking topography among contemporary marijuana users may be different than what was observed in 1988. A study of 20 marijuana users by McClure and colleagues in 2012 showed that puff volume and puff duration decreased between the first and last puffs of a joint, with an average puff volume between 51 and 61 ml and an average puff duration of 1.3 seconds (90); both measures are less than was observed by Wu and colleagues almost a quarter century prior. McClure and colleagues did not report inhaled volumes or breath hold time.

Differences in the Quantity of Smoked Plant Matter

One pack of cigarettes contains, on average, 14.6 g loose tobacco (91). Estimates for the average amount of marijuana per joint range from 0.32 g (92) to 0.66 g (93). Exposure to one pack-year of tobacco—one pack per day for one year—amounts to exposure to smoke from 5,329 g loose tobacco. Exposure to one joint-year—one joint per day for one year—amounts to exposure to smoke from 120 to 240 g of marijuana. Grossly, one pack-year of tobacco constitutes exposure to smoke from roughly 20-fold greater plant matter by mass than that consumed from exposure to one joint-year of marijuana. In general, tobacco users smoke much more tobacco by mass than marijuana users smoke marijuana by mass, even allowing for significant variability in joint, blunt, or bowl preparation. After 20 years of follow-up in CARDIA, the median number of tobacco pack-years was 7 among tobacco only users and 9 among tobacco and marijuana users, or 37.3 and 50.0 kg tobacco smoked, respectively; the median number of joint-years was 0.9 among marijuana only users and 1.5 among marijuana and tobacco users or, assuming 240 g marijuana per joint-year, 216 and 360 g marijuana smoked, respectively (43).

There is a large difference in combusted plant matter mass when comparing a tobacco pack-year with a marijuana joint-year or when comparing amounts consumed by heavy tobacco users with amounts consumed by heavy marijuana users. This makes comparisons of tobacco use and marijuana use challenging. However, the difference in exposure measurement points to a potential explanation for why marijuana use has been consistently associated with larger FVC whereas tobacco use has not: the effect of smoke on FVC may not be monotonic. Low amounts of smoke exposure, whether from marijuana or tobacco, might increase FVC, but high amounts of smoke exposure could have the opposite effect.

There are limited data supporting this explanation. Pletcher and colleagues found that in the CARDIA cohort, marijuana exposure had a nonlinear association with FVC; at low amounts of exposure, each joint-year was associated with a 20-ml increase in FVC, but at higher amounts of exposure—greater than 7 joint-years—there was no effect on FVC (43). When tobacco exposure was modeled as a categorical variable, a similar nonlinear relationship was observed. Exposure to 1–10 pack-years was associated with a 37-ml increase in FVC (95% CI, 12 to 61 ml), exposure to 11–20 pack-years was associated with only an 11-ml increase in FVC (95% CI, −20 to 41 ml), and exposure to more than 20 pack-years was associated with a 35-ml decrease in FVC (95% CI, −76 to 5 ml). Other studies have also observed that low amounts of tobacco smoke exposure are associated with larger FVC. In a study of 10,060 adolescents in six cities across the United States, 3,604 of whom reported ever smoking tobacco, FVC was larger among ever tobacco smokers than among never tobacco smokers (94). Although exposure to tobacco in this study was not reported in pack-years, in nearly half of smoking observations, participants reported smoking fewer than five cigarettes per day. More recently, lung volume measurements in tobacco smokers were found to have a nonlinear relationship with chronic obstructive pulmonary disease (COPD) severity; FVC was larger among those with mild COPD compared with both those without COPD and those with moderate COPD (95).

Furthermore, one might expect that the effect of marijuana exposure on FVC, when modeled as a linear function, might differ among never tobacco smokers and ever tobacco smokers. As the direction of effect might depend on the burden of exposure to tobacco smoke, a strong positive effect may be observed among never tobacco smokers, whereas an attenuated, or even negative, effect may be observed among ever tobacco smokers. This is what was found in the Dunedin study. Among never tobacco smokers, each joint-year of marijuana exposure was associated with a 19.8-ml increase in FVC (95% CI, 1.3 to 38.2 ml), but among ever tobacco smokers, each joint-year of marijuana exposure was associated with a 4.0-ml increase in FVC (95% CI, −4.0 to 12.1 ml) after adjustment for pack-years of tobacco exposure (44).

Conclusions

Studies have consistently shown that marijuana use is associated with an increase in FVC. Inferring causation from observational studies risks bias from confounding and measurement error, but threats to validity from bias are balanced with remarkable consistency in this observation among different populations and with different study designs, some with longitudinal data collection and robust adjustment for confounding exposures. How marijuana use could cause increased FVC is uncertain. Possible mechanisms include lung and chest growth and remodeling in the setting of mechanical strain from the act of inhaling marijuana smoke or, possibly, decreased lung elastic recoil from marijuana smoke. Why marijuana use, but not tobacco use, has been consistently associated with increased FVC is uncertain. There are differences in the composition of marijuana smoke compared with tobacco smoke, and there are differences in smoking topography between marijuana and tobacco users when inhaling marijuana and tobacco smoke; it is possible that some of these differences may

be causing apparent differential effects on FVC. Marijuana is also consumed in smaller quantities among marijuana users than tobacco is consumed among tobacco users; it is possible that smoke, whether from marijuana or tobacco, may have different effects on FVC depending on the degree of exposure. These possibilities need not be mutually exclusive.

What can be concluded from this survey of available data on the possible effect of marijuana use on FVC? For scientists, this surprising observation represents an opportunity to revisit our biological understandings of the effects of smoke, from marijuana or otherwise, on the respiratory system. Further physiologic, imaging, and pathological research is needed, as well as ongoing epidemiologic and behavioral investigation as patterns and methods of marijuana consumption change across the United States and the world. Future studies of marijuana use on lung function measurements, such as the FEV_1, should explore nonlinear effects as well as qualitative interaction with different degrees of tobacco use. For studies of causal inference on lung function, sufficient data likely exist to conclude that marijuana exposure has a probable causal effect on FVC, although the size and direction of effect may depend on other component causes, such as tobacco smoke exposure. For clinicians, the significance of marijuana's effect on FVC is not yet clear. Notably, an increase in FVC without a concomitant change in FEV_1 results in a lower FEV_1-to-FVC ratio, the clinical implication of which is uncertain. Although a larger FVC has been associated with lower mortality (96), an increase in FVC from marijuana—given the consistent association of marijuana smoke exposure to cough, sputum production, shortness of breath, and wheezing—should not be considered beneficial to any person's health. ■

Author disclosures are available with the text of this article at www.atsjournals.org.

References

1 Steigerwald S, Wong PO, Cohen BE, Ishida JH, Vali M, Madden E, *et al.* Smoking, vaping, and use of edibles and other forms of marijuana among U.S. adults. *Ann Intern Med* 2018;169:890–892.
2 Schauer GL, Njai R, Grant-Lenzy AM. Modes of marijuana use—smoking, vaping, eating, and dabbing: results from the 2016 BRFSS in 12 States. *Drug Alcohol Depend* 2020;209:107900.
3 Blackburn H, Brozek J, Taylor HL. Lung volume in smokers and nonsmokers. *Ann Intern Med* 1959;51:68–77.
4 Wilson RH, Meador RS, Jay BE, Higgins E. The pulmonary pathologic physiology of persons who smoke cigarettes. *N Engl J Med* 1960;262: 956–961.
5 Kuperman AS, Riker JB. The variable effect of smoking on pulmonary function. *Chest* 1973;63:655–660.
6 White JR, Froeb HF. Small-airways dysfunction in nonsmokers chronically exposed to tobacco smoke. *N Engl J Med* 1980;302: 720–723.
7 Pandey MR, Regmi HN, Neupane RP, Gautam A, Bhandari DP. Domestic smoke pollution and respiratory function in rural Nepal. *Tokai J Exp Clin Med* 1985;10:471–481.
8 Sherrill DL, Lebowitz MD, Knudson RJ, Burrows B. Smoking and symptom effects on the curves of lung function growth and decline. *Am Rev Respir Dis* 1991;144:17–22.
9 Behera D, Jindal SK, Malhotra HS. Ventilatory function in nonsmoking rural Indian women using different cooking fuels. *Respiration* 1994;61: 89–92.
10 Peters EJ, Esin RA, Immananagha KK, Siziya S, Osim EE. Lung function status of some Nigerian men and women chronically exposed to fish drying using burning firewood. *Cent Afr J Med* 1999;45:119–124.
11 Regalado J, Pérez-Padilla R, Sansores R, Páramo Ramirez JI, Brauer M, Paré P, *et al.* The effect of biomass burning on respiratory symptoms and lung function in rural Mexican women. *Am J Respir Crit Care Med* 2006;174:901–905.
12 Fullerton DG, Suseno A, Semple S, Kalambo F, Malamba R, White S, *et al.* Wood smoke exposure, poverty and impaired lung function in Malawian adults. *Int J Tuberc Lung Dis* 2011;15:391–398.
13 Kurmi OP, Devereux GS, Smith WC, Semple S, Steiner MF, Simkhada P, *et al.* Reduced lung function due to biomass smoke exposure in young adults in rural Nepal. *Eur Respir J* 2013;41:25–30.
14 Barbosa JV, Farraia M, Branco PTBS, Alvim-Ferraz MCM, Martins FG, Annesi-Maesano I, *et al.* The effect of fire smoke exposure on firefighters' lung function: a meta-analysis. *Int J Environ Res Public Health* 2022;19:16799.
15 White JD, Wyss AB, Hoang TT, Lee M, Richards M, Parks CG, *et al.* Residential wood burning and pulmonary function in the Agricultural Lung Health Study. *Environ Health Perspect* 2022;130:87008.
16 Hasin DS, Sarvet AL, Cerdá M, Keyes KM, Stohl M, Galea S, *et al.* US adult illicit cannabis use, cannabis use disorder, and medical marijuana laws: 1991–1992 to 2012–2013. *JAMA Psychiatry* 2017;74: 579–588.
17 Cerdá M, Mauro C, Hamilton A, Levy NS, Santaella-Tenorio J, Hasin D, *et al.* Association between recreational marijuana legalization in the United States and changes in marijuana use and cannabis use disorder from 2008 to 2016. *JAMA Psychiatry* 2020;77:165–171.
18 Martins SS, Segura LE, Levy NS, Mauro PM, Mauro CM, Philbin MM, *et al.* Racial and ethnic differences in cannabis use following legalization in US states with medical cannabis laws. *JAMA Netw Open* 2021;4:e2127002.
19 Weinberger AH, Wyka K, Goodwin RD. Impact of cannabis legalization in the United States on trends in cannabis use and daily cannabis use among individuals who smoke cigarettes. *Drug Alcohol Depend* 2022; 238:109563.
20 Patrick ME, Miech RA, Johnston LD, O'Malley PM. Monitoring the Future Panel Study annual report: national data on substance use among adults ages 19 to 60, 1976–2022. Ann Arbor, MI: Institute for Social Research, University of Michigan; 2023.
21 Tennant FS Jr, Prendergast TJ. Medical manifestations associated with hashish. *JAMA* 1971;216:1965–1969.
22 Vachon L, FitzGerald MX, Solliday NH, Gould IA, Gaensler EA. Single-dose effect of marihuana smoke. Bronchial dynamics and respiratory-center sensitivity in normal subjects. *N Engl J Med* 1973;288: 985–989.
23 Tashkin DP, Shapiro BJ, Frank IM. Acute pulmonary physiologic effects of smoked marijuana and oral (Delta)9 -tetrahydrocannabinol in healthy young men. *N Engl J Med* 1973;289:336–341.
24 Tashkin DP, Shapiro BJ, Frank IM. Acute effects of smoked marijuana and oral delta9-tetrahydrocannabinol on specific airway conductance in asthmatic subjects. *Am Rev Respir Dis* 1974;109:420–428.
25 Tashkin DP, Shapiro BJ, Lee YE, Harper CE. Effects of smoked marijuana in experimentally induced asthma. *Am Rev Respir Dis* 1975; 112:377–386.
26 Tashkin DP, Shapiro BJ, Lee YE, Harper CE. Subacute effects of heavy marihuana smoking on pulmonary function in healthy men. *N Engl J Med* 1976;294:125–129.
27 Cruickshank EK. Physical assessment of 30 chronic cannabis users and 30 matched controls. *Ann N Y Acad Sci* 1976;282:162–167.
28 Tashkin DP, Reiss S, Shapiro BJ, Calvarese B, Olsen JL, Lodge JW. Bronchial effects of aerosolized delta 9-tetrahydrocannabinol in healthy and asthmatic subjects. *Am Rev Respir Dis* 1977;115:57–65.
29 Williams SJ, Hartley JP, Graham JD. Bronchodilator effect of delta1-tetrahydrocannabinol administered by aerosol of asthmatic patients. *Thorax* 1976;31:720–723.
30 Hartley JP, Nogrady SG, Seaton A. Bronchodilator effect of delta1-tetrahydrocannabinol. *Br J Clin Pharmacol* 1978;5:523–525.
31 Sherrill DL, Krzyzanowski M, Bloom JW, Lebowitz MD. Respiratory effects of non-tobacco cigarettes: a longitudinal study in general population. *Int J Epidemiol* 1991;20:132–137.

32 Tan WC, Bourbeau J, Aaron SD, Hogg JC, Maltais F, Hernandez P, *et al.*; CanCOLD Collaborative Research Group; Members of the CanCOLD Collaborative Research Group not listed as authors. The effects of marijuana smoking on lung function in older people. *Eur Respir J* 2019;54:1900826.
33 Tashkin DP, Simmons MS, Sherrill DL, Coulson AH. Heavy habitual marijuana smoking does not cause an accelerated decline in FEV_1 with age. *Am J Respir Crit Care Med* 1997;155:141–148.
34 Tashkin DP, Calvarese BM, Simmons MS, Shapiro BJ. Respiratory status of seventy-four habitual marijuana smokers. *Chest* 1980;78:699–706.
35 Bloom JW, Kaltenborn WT, Paoletti P, Camilli A, Lebowitz MD. Respiratory effects of non-tobacco cigarettes. *Br Med J (Clin Res Ed)* 1987;295:1516–1518.
36 Moore BA, Augustson EM, Moser RP, Budney AJ. Respiratory effects of marijuana and tobacco use in a U.S. sample. *J Gen Intern Med* 2005; 20:33–37.
37 Aldington S, Williams M, Nowitz M, Weatherall M, Pritchard A, McNaughton A, *et al.* Effects of cannabis on pulmonary structure, function and symptoms. *Thorax* 2007;62:1058–1063.
38 Kempker JA, Honig EG, Martin GS. The effects of marijuana exposure on expiratory airflow: a study of adults who participated in the U.S. National Health and Nutrition Examination Study. *Ann Am Thorac Soc* 2015;12:135–141.
39 Barjaktarevic I, Cooper CB, Shing T, Buhr RG, Hoffman EA, Woodruff PG, *et al.* Effect of marijuana smoking on lung function change in older ever tobacco smokers. *Eur Respir J* 2022;60:2201133.
40 Najman JM, Bell S, Williams GM, Clavarino AM, Scott JG, McGee TR, *et al.* Do tobacco and cannabis use and co-use predict lung function: a longitudinal study. *Respir Med* 2023;208:107124.
41 Barjaktarevic I, Cooper CB, Shing T, Buhr RG, Hoffman EA, Woodruff PG, *et al.* Impact of marijuana smoking on COPD progression in a cohort of middle-aged and older persons. *Chronic Obstr Pulm Dis (Miami)* 2023;10:234–247.
42 Tilles DS, Goldenheim PD, Johnson DC, Mendelson JH, Mello NK, Hales CA. Marijuana smoking as cause of reduction in single-breath carbon monoxide diffusing capacity. *Am J Med* 1986;80:601–606.
43 Pletcher MJ, Vittinghoff E, Kalhan R, Richman J, Safford M, Sidney S, *et al.* Association between marijuana exposure and pulmonary function over 20 years. *JAMA* 2012;307:173–181.
44 Hancox RJ, Gray AR, Zhang X, Poulton R, Moffitt TE, Caspi A, *et al.* Differential effects of cannabis and tobacco on lung function in mid-adult life. *Am J Respir Crit Care Med* 2022;205:1179–1185.
45 Taylor DR, Poulton R, Moffitt TE, Ramankutty P, Sears MR. The respiratory effects of cannabis dependence in young adults. *Addiction* 2000;95:1669–1677.
46 Taylor DR, Fergusson DM, Milne BJ, Horwood LJ, Moffitt TE, Sears MR, *et al.* A longitudinal study of the effects of tobacco and cannabis exposure on lung function in young adults. *Addiction* 2002;97: 1055–1061.
47 Hancox RJ, Poulton R, Ely M, Welch D, Taylor DR, McLachlan CR, *et al.* Effects of cannabis on lung function: a population-based cohort study. *Eur Respir J* 2010;35:42–47.
48 Papatheodorou SI, Buettner H, Rice MB, Mittleman MA. Recent marijuana use and associations with exhaled nitric oxide and pulmonary function in adults in the United States. *Chest* 2016;149: 1428–1435.
49 Morris MA, Jacobson SR, Kinney GL, Tashkin DP, Woodruff PG, Hoffman EA, *et al.* marijuana use associations with pulmonary symptoms and function in tobacco smokers enrolled in the Subpopulations and Intermediate Outcome Measures in COPD Study (SPIROMICS). *Chronic Obstr Pulm Dis (Miami)* 2018;5:46–56.
50 Wenger DS, Triplette M, Shahrir S, Akgun KM, Wongtrakool C, Brown ST, *et al.* Associations of marijuana with markers of chronic lung disease in people living with HIV. *HIV Med* 2021;22:92–101.
51 Tan WC, Lo C, Jong A, Xing L, Fitzgerald MJ, Vollmer WM, *et al.*; Vancouver Burden of Obstructive Lung Disease (BOLD) Research Group. Marijuana and chronic obstructive lung disease: a population-based study. *CMAJ* 2009;180:814–820.
52 Sakhamuri S, Lutchmansingh F, Simeon D, Conyette L, Burney P, Seemungal T. Reduced forced vital capacity is independently associated with ethnicity, metabolic factors and respiratory symptoms in a Caribbean population: a cross-sectional study. *BMC Pulm Med* 2019;19:62.
53 Goodwin RD, Pacek LR, Copeland J, Moeller SJ, Dierker L, Weinberger A, *et al.* Trends in daily cannabis use among cigarette smokers: United States, 2002–2014. *Am J Public Health* 2018;108:137–142.
54 Lash TL, VanderWeele TJ, Haneuse S, Rothman KJ. Modern epidemiology. Amsterdam, the Netherlands: Wolters Kluwer; 2021.
55 Tashkin DP, Barjaktarevic I. How differential are the effects of smoking cannabis versus tobacco on lung function? *Am J Respir Crit Care Med* 2022;205:1136–1138.
56 Wu TC, Tashkin DP, Djahed B, Rose JE. Pulmonary hazards of smoking marijuana as compared with tobacco. *N Engl J Med* 1988;318:347–351.
57 Armour J, Donnelly PM, Bye PT. The large lungs of elite swimmers: an increased alveolar number? *Eur Respir J* 1993;6:237–247.
58 Courteix D, Obert P, Lecoq AM, Guenon P, Koch G. Effect of intensive swimming training on lung volumes, airway resistance and on the maximal expiratory flow-volume relationship in prepubertal girls. *Eur J Appl Physiol Occup Physiol* 1997;76:264–269.
59 Doherty M, Dimitriou L. Comparison of lung volume in Greek swimmers, land based athletes, and sedentary controls using allometric scaling. *Br J Sports Med* 1997;31:337–341.
60 Mehrotra PK, Verma N, Yadav R, Tewari S, Shukla N. Study of pulmonary functions in swimmers of Lucknow city. *Indian J Physiol Pharmacol* 1997;41:83–86.
61 Lazovic-Popovic B, Zlatkovic-Svenda M, Durmic T, Djelic M, Djordjevic Saranovic S, Zugic V. Superior lung capacity in swimmers: some questions, more answers! *Rev Port Pneumol (2006)* 2016;22: 151–156.
62 Bovard JM, Welch JF, Houghton KM, McKenzie DC, Potts JE, Sheel AW. Does competitive swimming affect lung growth? *Physiol Rep* 2018;6: e13816.
63 Rosser-Stanford B, Backx K, Lord R, Williams EM. Static and dynamic lung volumes in swimmers and their ventilatory response to maximal exercise. *Lung* 2019;197:15–19.
64 Rochat I, Côté A, Boulet LP. Determinants of lung function changes in athletic swimmers: a review. *Acta Paediatr* 2022;111:259–264.
65 ad hoc Statement Committee, American Thoracic Society. Mechanisms and limits of induced postnatal lung growth. *Am J Respir Crit Care Med* 2004;170:319–343.
66 Butler JP, Loring SH, Patz S, Tsuda A, Yablonskiy DA, Mentzer SJ. Evidence for adult lung growth in humans. *N Engl J Med* 2012;367:244–247.
67 Bouhuys A. Lung volumes and breathing patterns in wind-instrument players. *J Appl Physiol* 1964;19:967–975.
68 Gould WJ, Okamura H. Static lung volumes in singers. *Ann Otol Rhinol Laryngol* 1973;82:89–95.
69 Irzaldy A, Wiyasihati SI, Purwanto B. Lung vital capacity of choir singers and nonsingers: a comparative study. *J Voice* 2016;30:717–720.
70 Ksinopoulou H, Hatzoglou C, Daniil Z, Gourgoulianis K, Karetsi H. Respiratory function in vocal soloists, opera singers and wind instrument musicians. *Med Lav* 2016;107:437–443.
71 Heller SS, Hicks WR, Root WS. Lung volumes of singers. *J Appl Physiol* 1960;15:40–42.
72 Schorr-Lesnick B, Teirstein AS, Brown LK, Miller A. Pulmonary function in singers and wind-instrument players. *Chest* 1985;88:201–205.
73 Deniz O, Savci S, Tozkoparan E, Ince DI, Ucar M, Ciftci F. Reduced pulmonary function in wind instrument players. *Arch Med Res* 2006;37: 506–510.
74 Zuskin E, Mustajbegovic J, Schachter EN, Kern J, Vitale K, Pucarin-Cvetkovic J, *et al.* Respiratory function in wind instrument players. *Med Lav* 2009;100:133–141.
75 Fuhrmann AG, Franklin PJ, Hall GL. Prolonged use of wind or brass instruments does not alter lung function in musicians. *Respir Med* 2011;105:761–767.
76 Brzęk A, Famuła A, Kowalczyk A, Plinta R. Efficiency of lung ventilation for people performing wind instruments. *Med Pr* 2016;67:427–433.
77 Studer L, Schumann DM, Stalder-Siebeneichler A, Tamm M, Stolz D. Does trumpet playing affect lung function? A case-control study. *PLoS One* 2019;14:e0215781.
78 Gibson GJ, Pride NB, Davis J, Schroter RC. Exponential description of the static pressure-volume curve of normal and diseased lungs. *Am Rev Respir Dis* 1979;120:799–811.

79 Greaves IA, Colebatch HJ. Elastic behavior and structure of normal and emphysematous lungs post mortem. *Am Rev Respir Dis* 1980;121: 127–136.
80 Johnson MK, Smith RP, Morrison D, Laszlo G, White RJ. Large lung bullae in marijuana smokers. *Thorax* 2000;55:340–342.
81 Thompson CS, White RJ. Lung bullae and marijuana. *Thorax* 2002;57: 563.
82 Beshay M, Kaiser H, Niedhart D, Reymond MA, Schmid RA. Emphysema and secondary pneumothorax in young adults smoking cannabis. *Eur J Cardiothorac Surg* 2007;32:834–838.
83 Hii SW, Tam JD, Thompson BR, Naughton MT. Bullous lung disease due to marijuana. *Respirology* 2008;13:122–127.
84 Gargani Y, Bishop P, Denning DW. Too many mouldy joints—marijuana and chronic pulmonary aspergillosis. *Mediterr J Hematol Infect Dis* 2011;3:e2011005.
85 Fiorelli A, Accardo M, Vicidomini G, Messina G, Laperuta P, Santini M. Does cannabis smoking predispose to lung bulla formation? *Asian Cardiovasc Thorac Ann* 2014;22:65–71.
86 Bisconti M, De Palma A, Pacifici R, Rotolo MC, Pichini S, Brascia D, *et al.* Spontaneous pneumothorax secondary to bullous lung emphysema positive for cannabinoids upon toxicological examination. *J Clin Med* 2023;12:4956.
87 Moir D, Rickert WS, Levasseur G, Larose Y, Maertens R, White P, *et al.* A comparison of mainstream and sidestream marijuana and tobacco cigarette smoke produced under two machine smoking conditions. *Chem Res Toxicol* 2008;21:494–502.
88 Graves BM, Johnson TJ, Nishida RT, Dias RP, Savareear B, Harynuk JJ, *et al.* Comprehensive characterization of mainstream marijuana and tobacco smoke. *Sci Rep* 2020;10:7160.
89 Grassin-Delyle S, Naline E, Buenestado A, Faisy C, Alvarez JC, Salvator H, *et al.* Cannabinoids inhibit cholinergic contraction in human airways through prejunctional CB1 receptors. *Br J Pharmacol* 2014; 171:2767–2777.
90 McClure EA, Stitzer ML, Vandrey R. Characterizing smoking topography of cannabis in heavy users. *Psychopharmacology (Berl)* 2012;220: 309–318.
91 Agaku IT, Alpert HR. Trends in annual sales and current use of cigarettes, cigars, roll-your-own tobacco, pipes, and smokeless tobacco among US adults, 2002–2012. *Tob Control* 2016;25:451–457.
92 Ridgeway G, Kilmer B. Bayesian inference for the distribution of grams of marijuana in a joint. *Drug Alcohol Depend* 2016;165:175–180.
93 Mariani JJ, Brooks D, Haney M, Levin FR. Quantification and comparison of marijuana smoking practices: blunts, joints, and pipes. *Drug Alcohol Depend* 2011;113:249–251.
94 Gold DR, Wang X, Wypij D, Speizer FE, Ware JH, Dockery DW. Effects of cigarette smoking on lung function in adolescent boys and girls. *N Engl J Med* 1996;335:931–937.
95 Arjomandi M, Zeng S, Chen J, Bhatt SP, Abtin F, Barjaktarevic I, *et al.*; and the COPDGene and SPIROMICS Investigators. Changes in lung volumes with spirometric disease progression in COPD. *Chronic Obstr Pulm Dis (Miami)* 2023;10:270–285.
96 Burney PG, Hooper R. Forced vital capacity, airway obstruction and survival in a general population sample from the USA. *Thorax* 2011;66: 49–54.
97 Tashkin DP, Coulson AH, Clark VA, Simmons M, Bourque LB, Duann S, *et al.* Respiratory symptoms and lung function in habitual heavy smokers of marijuana alone, smokers of marijuana and tobacco, smokers of tobacco alone, and nonsmokers. *Am Rev Respir Dis* 1987; 135:209–216.
98 Vozoris NT, To TM, Ryan CM, Chow CW. Airways flow limitation in symptomatic adult cannabis smokers. *Int J Tuberc Lung Dis* 2021;25: 505–507.