Indeterminacy of Cannabis Impairment and Δ9-Tetrahydrocannabinol (Δ9-THC) Levels in Blood and Breath

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Abstract

Previous investigators have found no clear relationship between specific blood concentrations of D^9-tetrahydrocannabinol (D^9-THC) and impairment, and thus no scientific justification for use of legal “per se” D^9-THC blood concentration limits. Analyzing blood from 30 subjects showed D^9-THC concentrations that exceeded 5 ng/mL in 16 of the 30 subjects following a 12-hour period of abstinence in the absence of any impairment. In blood and exhaled breath samples collected from a group of 34 subjects at baseline prior to smoking, increasing breath D^9-THC levels were related to increasing blood levels in the absence of impairment, suggesting that single measurements of D^9-THC in breath, as is blood, are not related to impairment. When post-smoking duration of impairment was compared to baseline D^9-THC blood concentrations, subjects with the highest baseline D^9-THC levels tended to have the shortest duration of impairment. It was further shown that subjects with the shortest duration of impairment also tended to have the lowest incidence of horizontal gaze nystagmus at 3 h post-smoking. Finally, analysis of breath samples from these subjects revealed the presence of transient cannabinoids such as cannabigerol, cannabichromene, and D^9-tetrahydrocannabivarin during the peak impairment window, suggesting that these compounds may be key indicators of recent cannabis use through inhalation. In conclusion, these results provide further evidence that single measurements of D^9-THC in blood, and now in exhaled breath, do not correlate with impairment following inhalation, and that other cannabinoids may be key indicators of recent cannabis inhalation.

Introduction

Finding an objective measure of recent cannabis use that correlates with impairment has proven to be an elusive goal. In the United States, where the recreational use of cannabis has been legalized in 18 states and Washington, D.C. as of early 2022, some of these states have resorted to setting per se legal limits for D^9-tetrahydrocannabinol (D^9-THC) concentrations in blood, limits above which test subjects are considered to be legally impaired. For example, Illinois, Montana, and Washington have established a per se limit of 5 ng/mL, while Nevada and Ohio use a limit of 2 ng/mL [1]. In Colorado, a 5-ng/mL permissible inference standard is employed [1], meaning that a jury can legally presume that subjects testing at or above this level were impaired, unless evidence to the contrary can be provided by the defense. Published research in the last several years, however, has shown that there is no clear relationship between specific blood or oral fluid concentrations of D^9-THC and impairment [2–5]. In other words, there is currently no scientific justification for the use of per se legal limits for D^9-THC blood concentrations, leaving cannabis users in these states at risk of being wrongfully prosecuted for driving under the influence (DUI) of cannabis.

Exhaled breath has emerged as a potential alternative test matrix to blood and oral fluid for establishing recent cannabis use within the impairment window. While it has been known for nearly 40 years that D^9-THC can be detected in breath [6], only relatively recently has this matrix been explored for assessing recent cannabis use and impairment. Exhaled breath testing for recent cannabis use is predicated on a

short period of detection for D^9-THC within the impairment window, or approximately two to three hours. A study by Himes et al. suggested that D^9-THC is generally detectable in breath for only about two hours after smoking even in chronic users [7]; however, more recent studies have shown that D^9-THC can remain detectable in the breath up to several days following most recent use [8, 9].

Our recent publication describes the development of a new test for recent cannabis use and impairment based on two-point breath sampling, with or without a one-point confirmatory blood test, that can accurately detect whether a subject used cannabis through inhalation within the three-hour impairment window with no false positive results [10]. During that study, blood and exhaled breath samples were collected at baseline prior to smoking and at various time points up to four hours post-smoking and then analyzed by liquid chromatography high-resolution mass spectrometry (LC-HRMS) for D^9-THC and other cannabinoids. Impairment was evaluated through subject self-assessments as well as through physical assessments of horizontal gaze nystagmus (HGN). Using the data from our recent study [10], here we present evaluations of: (1) pre-smoking D^9-THC blood concentrations in relation to currently used per se legal limits; (2) post-smoking duration of impairment compared to baseline D^9-THC blood concentrations; (3) duration of impairment compared to the incidence of HGN; (4) the relationship between D^9-THC concentrations at baseline and at peak impairment in exhaled breath and blood; and (5) key cannabinoids detected in breath during the impairment window to assess the utility of single-point analyses of D^9-THC in blood and exhaled breath for detecting recent cannabis use within the impairment window.

Results

Clinical Study: Subject Demographics

A total of 74 subjects were recruited over a one-year period. The majority of subjects were recreational cannabis users, with some reporting both recreational and medicinal use. For most subjects, smoking and/or vaping was the primary route of use, while some subjects also reported use of cannabis edibles. When asked about frequency of use, most subjects reported daily use (14 out of the last 14 days). There was an approximate 3:1 ratio of males (56) to females (18), and the subjects ranged in age from 21 to 42 years, with an average age of 25.0 ± 4.5 years and a median age of 23 years. The subjects reported a mean cannabis use history of 9.0 ± 4.4 years.

Impairment does not Correlate to Specific D^9-THC Blood Concentrations

The scientific validity of legal “per se” limits for D^9-THC blood concentrations, at or above which test subjects are considered to be legally impaired, has recently been called into serious question. As shown in Figure 1, D^9-THC concentrations measured in blood prior to smoking exceeded 5 ng/mL (currently the legal limit in Illinois, Montana, and Washington) in 16 of 30 subjects (53.3%) in our study, and 25 of the

30 subjects (83.3%) had D^9-THC concentrations that exceeded 2 ng/mL (the legal limit in Nevada and Ohio), in the absence of impairment as determined by subject self-assessments. We previously showed that self-assessed impairment data corresponded well with evaluations of HGN used as a means of physically assessing impairment [10].

Duration of Impairment Inversely Related to Pre-Smoking D^9-THC Concentrations in Blood

Pre-smoking D^9-THC concentrations were evaluated in a total of 64 subjects, who were then stratified by their duration of impairment after smoking: 1 hour; 2 hours; 3 hours; >3 hours. There were 10 subjects from whom blood samples were not collected prior to smoking. Duration of impairment was based on subject self-assessments performed prior to smoking and at various time points post-smoking using a 10-point scale, where zero denoted no impairment and 10 denoted maximal impairment (incapacitation) for that individual. Some subjects did not finish smoking their cannabis cigarettes because they considered themselves completely impaired; however, all subjects experienced some impairment to the level where they felt they could no longer drive, which was the desired effect, but they were not maximally impaired. As shown in Figure 2, the duration of impairment post-smoking appeared to be inversely related to pre-smoking D^9-THC blood concentrations. While these differences were not statistically significant due to the high degree of variation in baseline D^9-THC concentrations, the results suggest that subjects with the highest baseline D^9-THC concentrations, indicative of chronic use, tended to have the shortest duration of impairment after smoking.

Relationship Between Duration of Impairment and the Incidence of HGN

A total of 44 subjects were evaluated for the presence of HGN as a means of physically assessing impairment prior to smoking and at various time points up to three hours post-smoking. Nystagmus refers to the involuntary jerking of the eyes as they gaze horizontally or vertically. Someone experiencing nystagmus is unaware of its occurrence. As shown in Figure 3, the duration of impairment was compared to the incidence of HGN at three hours post-smoking, at which time all but one subject (43/44) were evaluated. The results showed that subjects with the shortest duration of impairment tended to have the lowest incidence of HGN at three hours post-smoking.

Relationship Between Baseline D^9-THC Concentrations in Exhaled Breath and Blood

While we found no association between impairment and specific blood D^9-THC concentrations, a relationship between increasing baseline average D^9-THC concentrations in blood and increasing average concentrations in exhaled breath was observed in 34 subjects from whom both breath and blood samples were collected prior to smoking (see Table 1), in the absence of impairment. In 10 of the 44 subjects from whom both breath and blood samples were collected, no baseline samples were taken.

Those subjects found to have the lowest D^9-THC levels in their breath (undetectable; *N*=11) tended to have the lowest corresponding average concentration in blood, while subjects who had the highest average D^9-THC breath concentration also tended to have the highest average concentration in blood. For the 23 subjects who had detectable D^9-THC in breath, their corresponding blood concentrations were stratified into two groups: D^9-THC < 20 ng/mL (*N*=20) and D^9-THC >20 ng/mL (*N*=3), as shown in Table 1. The observed differences were not statistically meaningful due to a large variation in concentrations.

Table 1

Relationship between baseline D^9-THC concentrations in exhaled breath and blood (*N*=34).

	Average D^9-THC Concentrations (± SD)	
Subject Category	**Breath (ng/filter)**	**Blood (ng/mL)**
Undetectable baseline D^9-THC in breath	Not detected (*N*=11)	2.8 ± 1.5 (*N*=11)
Baseline blood D^9-THC < 20 ng/mL	0.2 ± 0.3 (*N*=20)	3.5 ± 2.8 (*N*=20)
Baseline blood D^9-THC >20 ng/mL	1.5 ± 2.0 (*N*=3)	54.1 ± 29.5 (*N*=3)

Relationship Between D^9-THC Concentrations in Exhaled Breath and Blood at Peak Impairment

The relationship between increasing D^9-THC concentrations in blood and exhaled breath observed at baseline prior to smoking was also observed post-smoking at the time of peak impairment in the same group of 34 subjects. As shown in Table 2, subjects who had the highest D^9-THC concentrations in breath and blood at baseline also tended to have the highest concentrations at peak impairment, although the differences were not significant. As previously reported [10], peak impairment occurred within the first hour after smoking in all subjects based on self-assessments. Together, the data in Tables 1 and 2 show that while individual measurements of D^9-THC in exhaled breath cannot be reliably associated with impairment, higher D^9-THC concentrations in breath both before and after smoking not surprisingly tend to be associated with higher blood concentrations. Figure 4 shows the relationship between breath and blood D^9-THC concentrations before and after smoking, with concentrations peaking within the first 20 min post-smoking and then rapidly declining to near baseline levels 3-4 hours post-smoking.

Table 2

Relationship between D^9-THC concentrations in exhaled breath and blood at peak impairment.

	Average D^9-THC Concentrations (± SD)	
Subject Category	**Breath (ng/filter)**	**Blood (ng/mL)**
Undetectable baseline D^9-THC in breath	403 ± 984 (*N*=10)[1]	51.9 ± 24.3 (*N*=5)[2]
Baseline blood D^9-THC < 20 ng/mL	217 ± 317 (*N*=20)	56.3 ± 46.3 (*N*=16)[3]
Baseline blood D^9-THC >20 ng/mL	1,070 ± 439 (*N*=3)	95.0 ± 29.7 (*N*=3)

[1]One outlier removed.

[2]Six subjects were not sampled at peak impairment.

[3]Four subjects were not sampled at peak impairment.

Detection of Key Cannabinoids in Breath

While the results of this study show that measuring D^9-THC by itself in blood or exhaled breath cannot be used as a reliable indicator of recent cannabis use within the impairment window, there are other cannabinoids that may serve as key indicators of recent use through inhalation. Exhaled breath samples were collected from a group of 44 subjects before and after smoking cannabis and analyzed for cannabinoid content. Table 3 shows the percent positivity of six cannabinoids prior to smoking (baseline), within the first 60 min post-smoking (peak impairment window), and more than 60 min post-smoking in subjects' exhaled breath samples. In particular, CBN, CBC, CBG, and D^9-THCV all had a much greater incidence in breath during the peak impairment window compared to pre-smoking. Interestingly, both CBC and D^9-THCV (shown in red) were detected in breath only during the peak impairment window.

Table 3
Presence of key cannabinoids in exhaled breath before and after smoking.

	Percent (%) Positivity		
Cannabinoid Parameters	**Baseline (Pre-smoking)[1]**	**≤ 60 minutes after smoking**	**>60 minutes after smoking[2]**
D^9-THC[3]	23/34 (67.6%)	40/40 (100%)	37/40 (92.5%)
CBN	1/34 (2.9%)	37/40 (92.5%)	4/40 (10.0%)
CBC	0/34 (0%)	39/40 (97.5%)	0/40 (0%)
CBG	2/34 (5.9%)	37/40 (92.5%)	1/40 (2.5%)
CBGA	4/34 (11.8%)	18/40 (45.0%)	4/40 (10.0%)
D^9-THCV	0/34 (0%)	36/40 (90.0%)	0/40 (0%)
[1]Pre-smoking samples were not collected from 10 subjects.			
[2]No data beyond 60 min post-smoking in 4 subjects.			
[3]Although D^9-THC was not detected in approximately one-third of subjects prior to smoking, other indicators of prior cannabis use, e.g., D^9-THCA, were detected at baseline in all subjects.			

Discussion

Previous studies have failed to demonstrate a clear relationship between impairment and specific concentrations of D^9-THC in blood or oral fluid [2–5]. In agreement with these studies, the results of the present work showed that a majority of a group of 30 test subjects had pre-smoking D^9-THC blood concentrations that exceeded the legal limits currently in place in five U.S. states (Illinois, Montana, Ohio, Nevada, and Washington), in the absence of impairment. The results also showed that post-smoking duration of impairment appeared to be inversely related to baseline blood D^9-THC concentrations, and that subjects with the shortest duration of impairment tended to have the lowest incidence of HGN three hours post-smoking. These findings provide further evidence that single measurements of specific D^9-THC blood concentrations do not correlate with impairment, and that the use of per se legal limits for D^9-THC is not scientifically justifiable at the present time.

Although it may seem counterintuitive, the inverse relationship between impairment duration and baseline D^9-THC blood concentration observed in the present study is consistent with what would be expected from chronic cannabis users who have developed a high degree of tolerance to the impairing effects D^9-THC. Ramaekers et al. showed that neurocognitive performance was significantly impaired after smoking

in occasional cannabis users compared to chronic, heavy users, indicating the development of tolerance [11, 12]. The development of tolerance may involve multiple pharmacodynamic mechanisms including the downregulation and desensitization of CB_1 receptors in various brain regions [13–15] and the recruitment of alternate neural networks to compensate for the impairing effects of D^9-THC during the performance of neurocognitive tasks [16, 17]. It has also been shown that the development of tolerance to D^9-THC may reduce the sensitivity of standardized field sobriety tests in the detection of cannabis impairment [18]. It is therefore not surprising that the subjects in present study, most of whom were chronic, daily cannabis users, presented with high blood concentrations of D^9-THC prior to smoking, in the absence of impairment, that the duration of impairment tended to be shorter in subjects with higher baseline D^9-THC concentrations, and that the lowest incidence of HGN at three hours post-smoking tended to be observed in subjects with the shortest duration of impairment, all of which are indicative of the development of tolerance.

When D^9-THC concentrations in exhaled breath were compared to those in blood at baseline and during peak impairment after smoking, increasing blood concentrations were generally associated with increasing breath concentrations. This result in exhaled breath at baseline in the absence of impairment suggests, just as is the case with D^9-THC concentrations in blood, single measurements of D^9-THC in breath cannot be used to establish impairment. Our findings are consistent with others who have shown that D^9-THC can be detected in breath up to several days since last use [8, 9]. Because the leading technologies for breath-based testing for recent cannabis use [8, 19] rely solely on the detection of D^9-THC, this could potentially result in false positive test outcomes due to the presence of D^9-THC in breath outside of the impairment window. It may be that other cannabinoids such as D^9-THCV and CBC, which were detected in breath only during the impairment window in the present study, are more suitable key indicators of recent cannabis use associated with impairment.

In conclusion, we present further evidence that single measurements of D^9-THC in blood cannot establish impairment, that single measurements of D^9-THC in exhaled breath likewise do not correlate with impairment, and that D^9-THCV and CBC may be key indicators of recent cannabis use through inhalation within the impairment window.

Materials And Methods

Clinical Study

A total of 74 subjects were recruited to perform a study designed to develop a test that confirms recent use of inhaled cannabis within the impairment window as previously described [10]. All subjects received financial compensation for their participation. The study was performed under a clinical protocol approved by the Cancer Immunotherapy Research Institute IRB (assurance #FWA00029851), and all research activities were conducted in accordance with the Declaration of Helsinki. Written informed

consent was obtained from all subjects prior to their participation, and a copy of the signed informed consent form was provided to each subject.

Inclusion Criteria

To be included, a subject must have been a male or female cannabis user at least 21 years of age. Prior to their scheduled participation, they must have used within the previous 24 hours, but not within the last 12 hours. Upon entry, subjects were asked to complete a questionnaire requesting their age, sex, race, height, weight, cannabis use history (time since last use, number of days used in the last 14 days, how often they use cannabis, number of years of cannabis use), their primary route of cannabis use, whether or not they use tobacco and alcohol, and any medications or supplements they are taking.

Cannabis Administration

Each subject was given a single cannabis cigarette and instructed to smoke as much of it as possible within a 10-min period. Cigarettes containing 500 mg of dried cannabis flower with a Δ^9-THC content ranging from 8.5 to 28.4% were prepared immediately before each smoking session. Cannabis supplies were legally obtained from licensed retail establishments in the Sacramento, CA region. A wide variety of chemovars was included to account for the variability in potencies available in numerous cannabis retail establishments in the various U.S. states where recreational and/or medicinal cannabis has been legalized.

Blood Draw Schedule

Blood samples were obtained from all 74 subjects. To establish baseline cannabinoid levels, capillary blood samples were collected prior to smoking. Post-smoking blood samples were collected immediately after smoking and then at 20, 40, 60, 80, 100, 120, 140, 160, 180, and 200 min post-smoking. Capillary blood (50-100 µL) was collected into BD Microtainer tubes containing lithium heparin anticoagulant (Thermo Fisher Scientific; Waltham, MA) after pricking subjects' fingers using 17-gauge lancets (McKesson Medical-Surgical Inc., Richmond, VA). Some capillary blood samples were drawn using automated collection devices from Tasso, Inc. (Seattle, WA) and Seventh Sense Biosystems, Inc. (Medford, MA) equipped with sample reservoirs containing lithium heparin. These devices are designed to draw approximately 100-150 µL of whole blood over a period of 1-3 min.

Breath Collection Schedule

Breath samples were obtained from a total of 44 subjects. The other 30 subjects had only blood samples collected because the original study design was to develop a blood-based cannabis recent use test. Data

from these first 30 subjects showed that an additional component, exhaled breath, was needed to more accurately detect recent cannabis use within the impairment window.

To establish baseline cannabinoid levels, breath samples were collected prior to smoking. Post-smoking breath samples were collected immediately after smoking, and then at 10, 20, 30, 40, 50, 60, 80, 120, 180, and 240 min post-smoking in the first 35 subjects. In the last nine subjects, back-to-back breath samples were collected at 20 and 40 min post-smoking. Breath sample collection devices were provided by Sensabues AB (Stockholm, Sweden). These self-contained, single-use devices contain an electrostatic polymer filter and are designed to collect about 20 L of exhaled breath through normal breathing. During sample collection, subjects were seated and instructed to blow through the device until the attached bag was fully inflated. The time required for sample collection was approximately 2-3 minutes. No instances of hyperventilation or other breathing abnormalities were observed. Devices were kept sealed in their original packaging until immediately before use to prevent contamination and used according to the manufacturer's instructions. The smoking room was well ventilated and allowed to clear for at least 24 hours prior to each subject smoking session. Immediately after sample collection, the devices were resealed, removed from the collection area, and held at room temperature (20-25°C). All samples were extracted and analyzed within 24 hours of collection.

Self-Assessment of Impairment

All 74 subjects were asked to self-assess their level of impairment before smoking and at each designated time point after smoking based on a scale ranging from 0 (no impairment) to 10, which denoted maximal impairment (incapacitation) for that individual. To normalize, impairment data were expressed as a percentage relative to each individual subject's maximum reported impairment level.

Physical Assessment of Impairment: Horizontal Gaze Nystagmus

In this study, a subset of 44 subjects were evaluated for horizontal gaze nystagmus (HGN) as a physical indicator of impairment. Horizontal gaze nystagmus refers to the involuntary movement or jerking of the eyes as they gaze to either side, and it is a component of standardized field sobriety testing [20]. In this particular test, subjects are asked to keep their head still and follow a slowly moving horizontal object positioned in front of their face using their eyes only. Both eyes are observed for lack of smooth pursuit, nystagmus at maximum eye deviation (45°), and the onset of nystagmus prior to a 45° deviation. The presence or absence of resting nystagmus is also noted.

Analytical Methods

Chemicals and Reagents

Six of the seven cannabinoid analytes [D^9-THC, cannabinol (CBN), cannabigerol (CBG), cannabigerolic acid (CBGA), D^9-tetrahydrocannabinolic acid A (D^9-THCA), and D^9-tetrahydro-cannabivarin (D^9-THCV)] and the internal standard (IS; D^9-THC-D_3) were obtained as certified reference materials (CRMs) manufactured by Cerilliant (Round Rock, TX). Cannabichromene (CBC) was obtained as a CRM from Cayman Chemical (Ann Arbor, MI). When not in use, concentrated stock solutions of these agents and working solutions made therefrom were stored at –20°C.

Acetonitrile, formic acid, methanol, and *n*-hexane were purchased from Thermo Fisher Scientific and were of LC/MS grade. Ethyl acetate (Acros Organics) was purchased from Thermo Fisher Scientific and was of spectroscopy grade (>99.5%). High purity water (18.2 MΩ) required for preparing the mobile phase and for sample extraction was produced using an EMD Millipore Simplicity water purification system. When not in use, these agents were stored at room temper-ature (20-25°C). Nitrogen (N_2), supplied as a cryogenic liquid in a 230L dewar at a purity of 99.998%, or as compressed nitrogen gas at a purity of 99.999% in T-type cylinders, was obtained from Praxair (Danbury, CT).

Analysis of Cannabinoids in Exhaled Breath

A previously validated LC-HRMS analytical method for the quantification of the cannabinoids D^9-THC, CBN, CBC, and D^9-THCV in exhaled breath was used for the analysis of study samples. Additional cannabinoids analyzed included D^9-THCA, CBG, and CBGA. For the preparation of calibration standards, sufficient quantities of the matrix (breath collection devices) were obtained from SensAbues AB. Breath collection devices were kept at room temperature (20-25°C) within their original packaging to prevent contamination.

Concentrated standard calibration solutions were prepared in methanol at 37.5, 75, 150, 375, 750, and 1,500 ng/mL of all cannabinoids combined. Following extraction and reconstitution, final standard concentrations were 2.5, 5.0, 10, 25, 50 and 100 ng/mL, equivalent to approximately 0.2, 0.4, 0.8, 1.9, 3.8, and 7.5 ng/breath filter. The IS solution was prepared in methanol at a concentration of 75 ng/mL. To prepare calibration standards for extraction, 5 µL of the IS working solution and 5 µL of the appropriate calibration standard solution were added directly onto the corresponding filter pad inside the breath collection device. After extraction, the final concentration of the IS was 5 ng/mL (75 µL final volume). Study samples were prepared by spiking with 5 µL IS solution.

Extraction of cannabinoids from breath collection devices was performed as previously described [10]. Briefly, a total of 7 mL methanol were aliquoted through each device and filter housing into glass sample collection tubes. The sample breath collection devices were then removed and the glass tubes were placed in an N-Evap Model 112 analytical nitrogen evaporator (Organomation Associates, Berlin, MA). The eluate was evaporated to dryness under a gentle stream of nitrogen gas, with the water bath

temperature set to approximately 50°C. After evaporation, the samples were cooled to room temperature and reconstituted in 75 µL of a solution containing 75% acetonitrile and 25% water with 0.1% formic acid. The samples were then transferred to a glass microinsert-equipped autosampler vial and placed in the autosampler compartment for analysis according to the method. The chromatographic conditions for the analysis of cannabinoids in exhaled breath were the same as previously described [21].

Analysis of Cannabinoids in Blood

Extraction and analysis of D^9-THC and other cannabinoids in whole blood was performed according to a validated method as previously described [21]. Briefly, 50 µL of each sample was mixed with 100 µL of high-purity water in a 1.5-mL microcentrifuge tube and spiked with 5.0 µL of IS solution. To extract, 500 µL of a solution containing 90% *n*-hexane and 10% ethyl acetate (v/v) was added to each sample, followed by vortexing for 30 sec. Samples were then centrifuged at 9,300 rcf for 10 min. The supernatant was transferred to a 16 mm x 125 mm glass tube and evaporated to dryness under a gentle stream of nitrogen at 50°C. Samples were then reconstituted in 75 µL of a solution composed of 65% acetonitrile, 35% water, and 0.1% formic acid and analyzed by LC-HRMS. Supplies of whole blood needed to prepare calibration standards were obtained from a reliable, cannabis-free donor and kept refrigerated (2-8°C) for up to six weeks.

The LC-HRMS system consisted of a Thermo Scientific Vanquish ultra-high-performance liquid chromatography (UHPLC) system and a Thermo Scientific Q Exactive mass spectrometer. All analytical data were collected and processed using TraceFinder version 4.1 software (Thermo Fisher Scientific). The mass spectrometer and UHPLC system were configured as previously described [21].

Declarations

Data Availability

All datasets generated and/or analyzed during the present study are either available in the main text and supplementary materials, or can be obtained from the corresponding author on reasonable request.

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Author Contributions

MWD conceived and designed the study; MWD and GTW acquired, analyzed, and interpreted the data; GTW drafted the manuscript; MWD and GTW reviewed and edited the manuscript. All authors approved the submitted version of the manuscript and agree to be personally accountable for their own contributions.

Competing Interests

MWD and GTW are the inventors of the recent cannabis use testing methodology (patents PCT/US2019/028298, PCT/US2021/056591, and 63/185,263 pending) described in the present work, and both authors are founders of RCU Labs, Inc. GTW is additionally an employee of RCU Labs, Inc. MWD is also a DEA-registered Schedule I researcher (RD0543163) with ImmunoTess, Inc. conducting clinical work with the Cancer Immunotherapy Research Institute.

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Figures

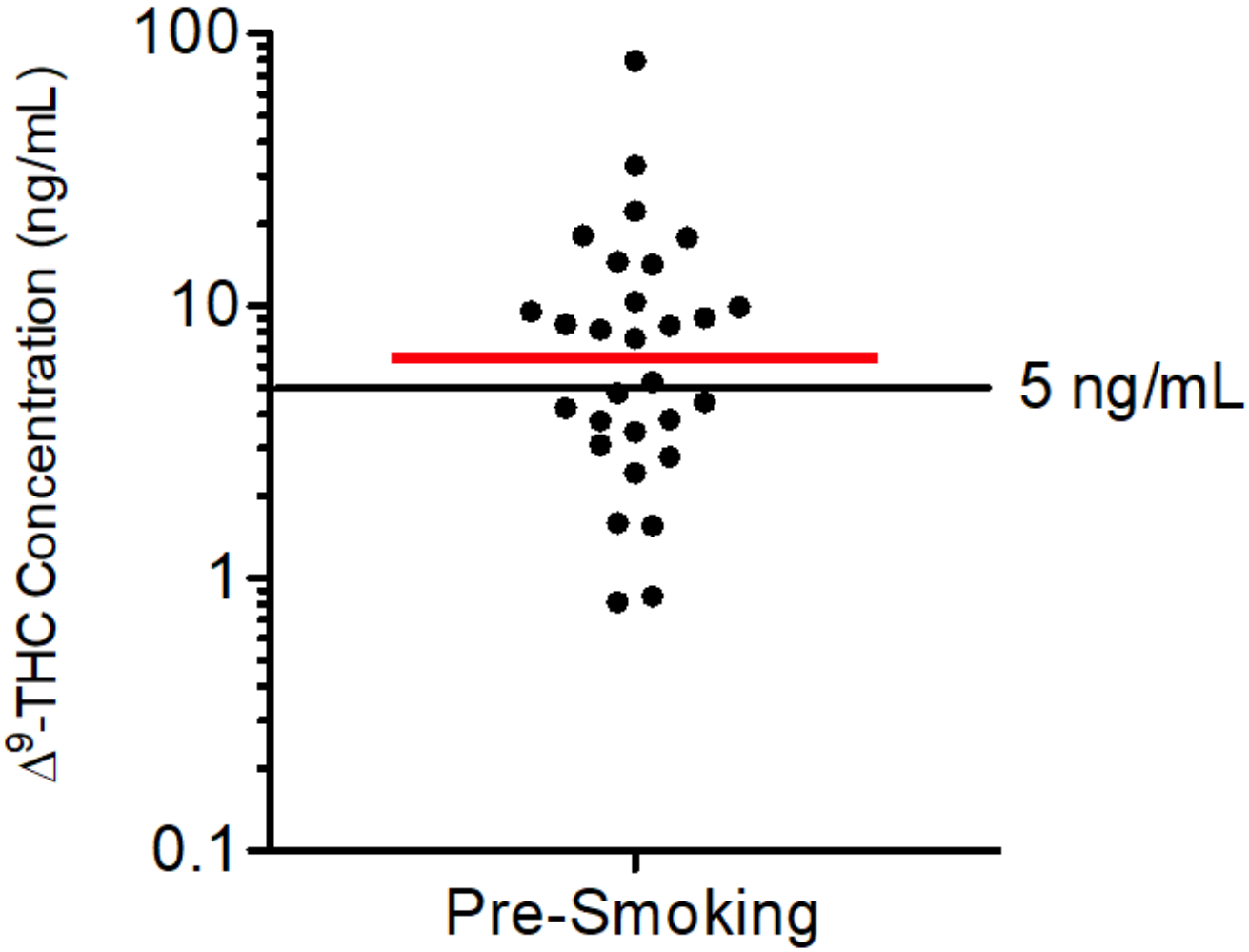

Figure 1

Baseline D^9-THC blood concentrations in a group of 30 subjects.

Pre-smoking (baseline) D^9-THC blood concentrations were evaluated by LC-HRMS in a group of 30 subjects prior to smoking a 500-mg cannabis cigarette. The horizontal red bar indicates the median concentration (6.4 ng/mL), and the horizontal black bar at 5 ng/mL indicates a common legal per se D^9-THC blood concentration limit. One subject not shown (D^9-THC not detected).

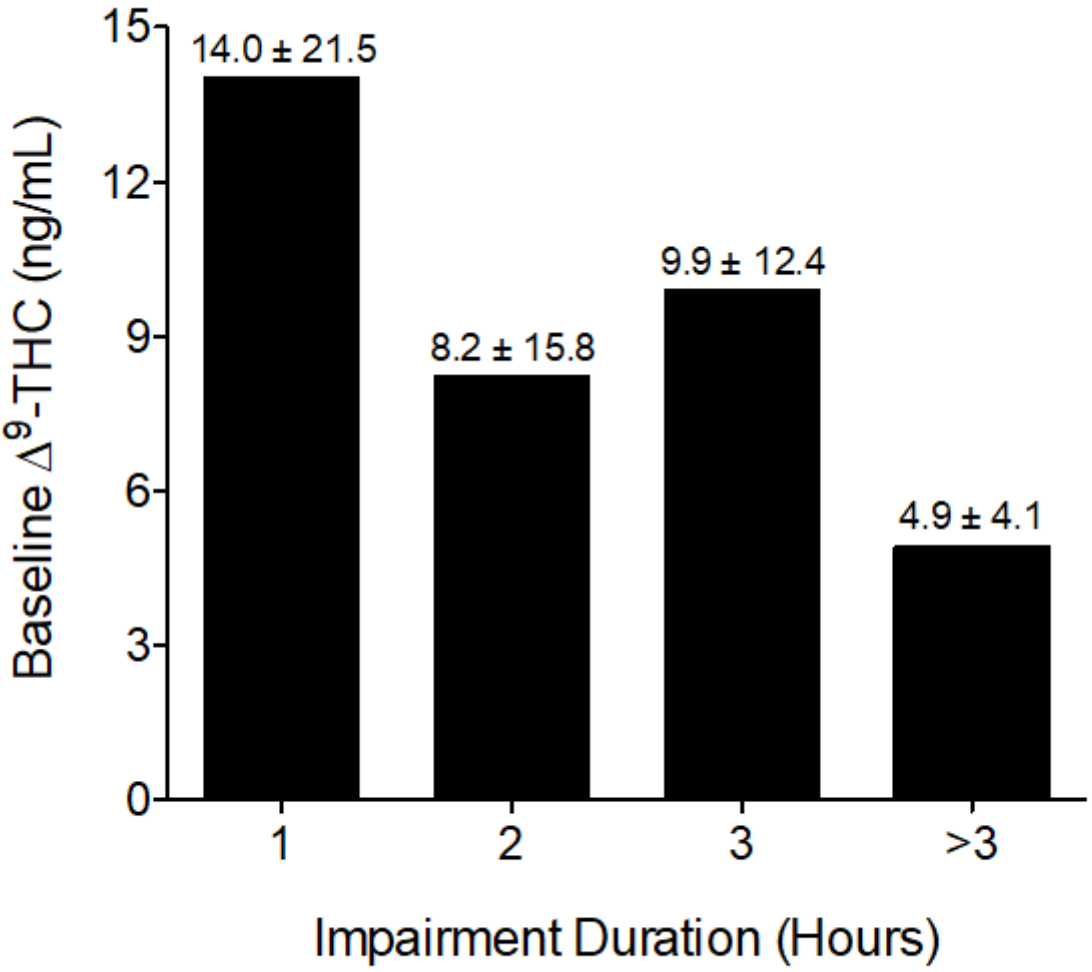

Figure 2

Post-smoking duration of impairment compared to baseline D^9-THC blood concentration in 64 subjects.

As determined by self-assessment, subjects were stratified by duration of impairment [1 h (*N*=19), 2 h (*N*=24), 3 h (*N*=17), >3 h (*N*=4)] after smoking a 500-mg cannabis cigarette. Mean D^9-THC concentration (± SD) is shown above each bar.

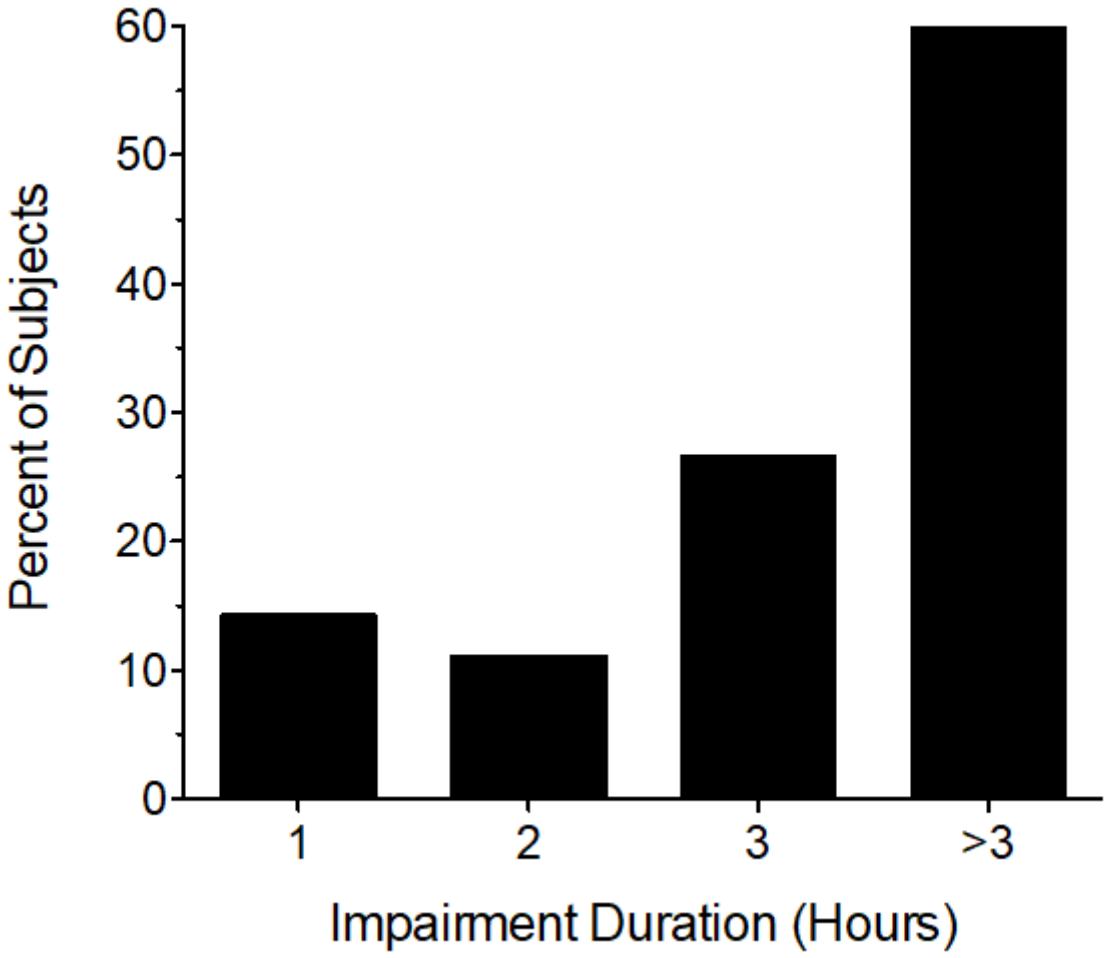

Figure 3

Relationship between duration of impairment and the incidence of nystagmus.

A total of 44 subjects were assessed for nystagmus prior to smoking and at various time points up to three hours post-smoking (43/44 subjects were evaluated at three hours post-smoking). As determined by self-assessments, subjects were stratified by duration of impairment, 1 hour (*N*=14), 2 hours (*N*=9), 3 hours (*N*=15), or >3 hours (*N*=5), and the incidence of nystagmus at three hours post-smoking was calculated.

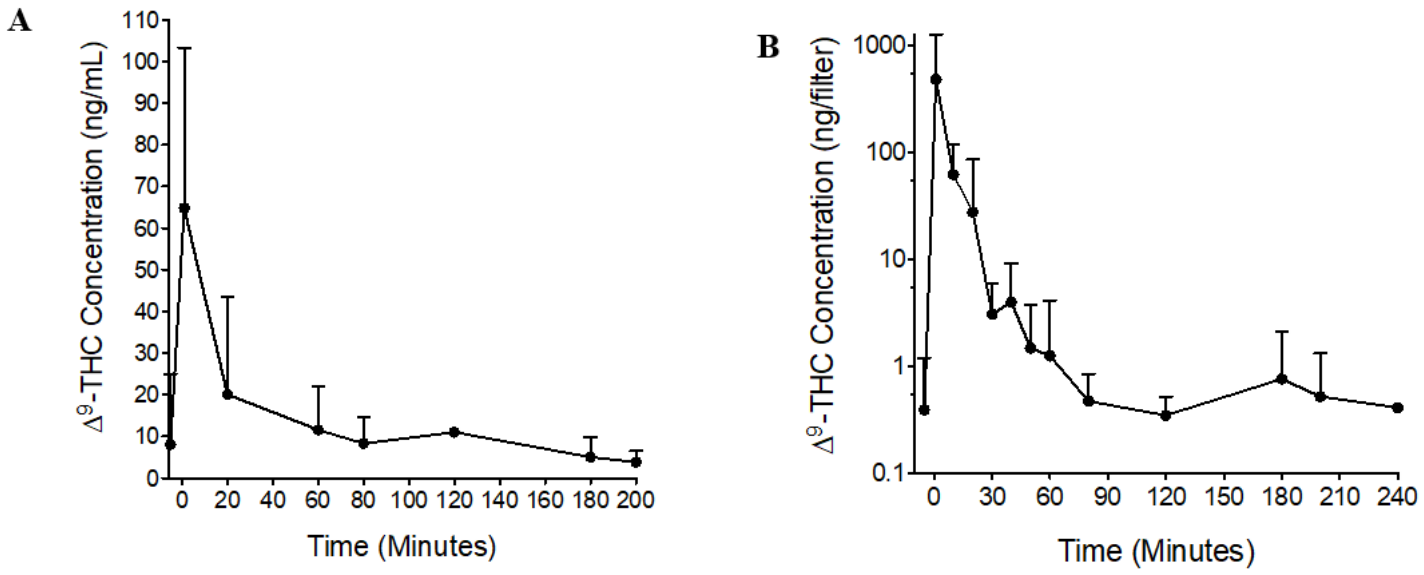

Figure 4

Relationship between blood and breath D^9-THC concentrations before and after smoking in 34 subjects.

Average (+ SD) D^9-THC concentrations are shown in (A) blood (ng/mL) and (B) breath (ng/filter). Lack of error bars indicates *N*=2. The number of subjects at each time point varies due to non-detection (ND) of D^9-THC, no sample (NS) collected, and removal of outliers. For blood, *N*=32 prior to smoking (2 ND), 24 at 1 min post-smoking (10 NS), 25 at 20 min (9 NS), 33 at 60 min (1 outlier), 8 at 80 min (24 NS, 1 ND, 1 outlier), 2 at 120 min (32 NS), 22 at 180 min (8 NS, 2 ND, 2 outliers), and 12 at 200 min (21 NS, 1 ND). For breath, *N*=23 prior to smoking (11 ND), 24 at 1 min post-smoking (9 NS, 1 outlier), 11 at 10 min (23 NS), 32 at 20 min (2 outliers), 11 at 30 min (23 NS), 20 at 40 min (14 NS), 11 at 50 min (23 NS), 25 at 60 min (9 NS), 10 at 80 min (23 NS, 1 ND), 3 at 120 min (31 NS), 26 at 180 min (7 NS, 1 ND), 3 at 200 min (30 NS, 1 ND), and 2 at 240 min (32 NS).