

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/320095257>

# Evaluation of an activated carbon based deactivation system for the disposal of highly abused opioid medications

Article in *Drug Development and Industrial Pharmacy* · September 2017

DOI: 10.1080/03639045.2017.1386199

CITATIONS

0

READS

31

7 authors, including:



**Pooja Nazar Bakshi**  
Mercer University

7 PUBLICATIONS 12 CITATIONS

[SEE PROFILE](#)



**Mahima Manian**  
Mercer University

3 PUBLICATIONS 4 CITATIONS

[SEE PROFILE](#)



**Ajay Banga**  
Mercer University

188 PUBLICATIONS 4,075 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Anti Fungal project [View project](#)



Microneedles [View project](#)



## Evaluation of an activated carbon-based deactivation system for the disposal of highly abused opioid medications

Xinyi Gao, Pooja Bakshi, Sindhu Sunkara Ganti, Mahima Manian, Andrew Korey, William Fowler & Ajay K. Banga

To cite this article: Xinyi Gao, Pooja Bakshi, Sindhu Sunkara Ganti, Mahima Manian, Andrew Korey, William Fowler & Ajay K. Banga (2018) Evaluation of an activated carbon-based deactivation system for the disposal of highly abused opioid medications, Drug Development and Industrial Pharmacy, 44:1, 125-134, DOI: [10.1080/03639045.2017.1386199](https://doi.org/10.1080/03639045.2017.1386199)

To link to this article: <https://doi.org/10.1080/03639045.2017.1386199>



Accepted author version posted online: 28 Sep 2017.  
Published online: 17 Oct 2017.



Submit your article to this journal [↗](#)



Article views: 71



View Crossmark data [↗](#)

RESEARCH ARTICLE



## Evaluation of an activated carbon-based deactivation system for the disposal of highly abused opioid medications

Xinyi Gao<sup>a</sup>, Pooja Bakshi<sup>a</sup>, Sindhu Sunkara Ganti<sup>a</sup>, Mahima Manian<sup>a</sup>, Andrew Korey<sup>b</sup>, William Fowler<sup>b</sup> and Ajay K. Banga<sup>a</sup>

<sup>a</sup>Department of Pharmaceutical Sciences, Mercer University, Atlanta, GA, USA; <sup>b</sup>Verde Environmental Technologies Inc., Burnsville, MN, USA

### ABSTRACT

**Context:** The improper disposal of unused prescription opioids has a potential for abuse as well as environmental contamination. Consequently, there is an imperative need for an environmentally safe, convenient, and effective drug disposal system.

**Objective:** The objective of this study is to analyze the deactivation efficiency of the disposal system employing four model opioid drugs of high abuse potential.

**Methods:** The deactivation system used in this investigation is an activated granular carbon based disposal system in the form of a pouch, which can be used to safely and effectively deactivate unused or expired medications. HPLC method validation for each drug was performed prior to analyzing drug content in the deactivation study. Opioid drugs in different dosage forms were added to individual pouches in the presence of warm water. Pouches were shaken and sealed, then stored at room temperature. The deactivation efficiency of the system was tested by collecting samples at different time points up to 28 d.

**Results:** An average of 98.72% of medications were adsorbed by activated carbon within 8 h and continued to do so over time. At the end of the 28-d study, more than 99.99% of all drugs were deactivated. In the desorption study, almost no drug leached out from the activated carbon in larger volume of water and less than 1.3% leached out on extraction with ethanol.

**Conclusion:** This unique drug disposal system successfully adsorbed and deactivated the model opioid medications by the end of 28 d, offering a safe and convenient route of disposal of unused or residual opioid drugs.

### ARTICLE HISTORY

Received 9 April 2017  
Revised 13 September 2017  
Accepted 18 September 2017

### KEYWORDS

Opioids; drug disposal system; deactivation; activated carbon

### Introduction

The abuse and misuse of prescription drugs has become a serious health, safety, and environmental problem over the last two decades in the United States. An estimated 54 million Americans misuse prescription drugs at least once during their lifetime [1]. In the late 1990s, the treatment of chronic pain with prescription opioid medications became prevalent and by the year 2012, almost 259 million prescriptions were written for opioids, which was approximately equal to the adult population in the US [2].

Opioids exert analgesic effects and euphoria by binding to opioid receptors in the nervous system, gastrointestinal tract, and other organs throughout the body to inhibit neurotransmitter release [3]. Common side effects associated with opioid use include sedation, dizziness, nausea, vomiting, constipation, and respiratory depression. Repeated exposure to increasing doses of opioids alters the brain such that it functions normally when opioids are in the system and abnormally when withdrawn from the opioids. Results of this alteration are opioid tolerance (the need for higher doses to achieve the same opioid effect) and drug dependence (susceptibility to withdrawal symptoms). Repeated administration desensitizes the opioid receptor making them less responsive to opioid stimulation and thereby leading to tolerance. Opioid withdrawal is one of the most compelling factors that drive opioid dependence/addictive behaviors and can eventually lead to fatal consequences due to overdose [4]. Today in the United

States, nearly half of all the opioid overdose deaths involve a prescription opioid and in 2015, more than 15,000 people died from prescription opioids related overdose [5]. Deaths due to overdose of opioid analgesics has now exceeded deaths involving heroin and cocaine abuse [6].

The dramatic increase in the number of prescriptions for opioid therapy has led to an increase in the rate of illicit use and misuse of these drugs. Hoarding and non-adherence to the prescribed course of treatment contributes to unintentional risk of exposure and additional waste of unused or expired opioids in the medicine cabinets which is a very common source for non-medicinal use of these drugs. Based on the data from the National Survey on Drug Use and Health from 2008 to 2011, more than 50% of non-medical users obtained opioids from friends and relatives for free [7].

US Food and Drug Administration (FDA) recommends the disposal of unused medication by mixing with unpalatable substances such as cat litter or used coffee grounds and to place this mixture in a sealed container followed by direct disposal in normal household trash [8]. Medicines discarded in this manner may end up in the landfill and contaminate freshwater resources and promote drug resistance in bacteria [9]. FDA also suggests flushing of drugs in order to prevent their misuse but this may also result in these medications entering the water system and thereby affecting not only marine life but also animal and human life [10]. Even though direct excretion of pharmaceuticals via human waste is considered the primary route by which drugs enter the environment,

disposal of unwanted medications by flushing into the sewers is also a significant source [11]. Martinez et al. monitored 100 organic contaminants in municipal sewage treatment plants and found anti-inflammatory and analgesic drugs to be the most commonly encountered contaminants [12]. It is therefore critically important to dispose such unwanted pharmaceuticals safely in order to protect both human life and the environment.

Take-back programs have the potential to prevent the misuse of leftover pharmaceuticals and have been suggested as a straightforward way to prevent pollution. However, there are several disadvantages including the restraint on returning controlled substances like opioids, scavenging from the disposal location, lack of adequate and sustained funding and low percentage of consumer participation [13]. Moreover, the collected drugs from take-back programs are disposed by incineration or landfilling which contribute to toxic air emissions or potential contamination of groundwater due to aging and leakage from the leachate that can last for decades or even centuries [14].

Waybright et al. evaluated the efficacy of a commercial drug disposal product composed from a slurry of activated carbon in an 8 oz bottle to deactivate different types of drugs and the results showed that more than 98% of the active ingredients were sequestered after 48 h [15]. The system does not demonstrate its ability to prevent leaching of drugs from the disposal system in presence of large quantities of water or organic solvents.

In face of all the risks associated with opioid abuse, the resulting environmental risks and previous research, there is an imperative need to provide a simple and cost-effective way of drug disposal to improve adherence in public and prevent environmental contamination. Our study aims to furnish this urgent need by using an activated carbon based deactivation system to deactivate opioids of high abuse potential. Our drug disposal system comprises of a sealable outer pouch and an inner water permeable pouch which contains 15 g of proprietary activated carbon which utilizes patented MAT<sub>12</sub><sup>®</sup> Molecular Adsorption Technology to give significant amount of surface area to insure sufficient adsorption and retention properties [16]. Deactivation is referred to as inactivation or removing the effectiveness of the drug. In our study, this is achieved by adsorption of the pharmaceutically active ingredient by activated carbon thereby rendering them inactive and unapproachable for misuse.

The objective in the present investigation was to use four model opioid drugs including; morphine sulfate, methadone hydrochloride, hydromorphone hydrochloride, and meperidine hydrochloride to test the deactivation efficiency of this activated carbon drug disposal system. Morphine is the most abundant alkaloid found in opium which is used before and after surgical procedures to relieve severe pain and is regarded as the gold standard of analgesics [17]. However, morphine is a highly addictive substance which can cause intense physical and psychological dependence and lead to abuse and eventually overdose death by respiratory depression. As a derivative of morphine, hydromorphone (semi-synthetic opioid) has similar pharmacological action to morphine but 6–8 times more potent than morphine and its physical and psychological dependence results in its high abuse potential [18]. Meperidine hydrochloride is a synthetic opioid with multiple pharmacological actions similar to morphine, however, may lead to fatal reactions in patients who have received monoamine oxidase inhibitors [19]. Methadone is a synthetic opioid that can be used in the management of opioid addiction due to its long half-life, but its use is associated with a high proportion of overdose deaths [20]. The aim was further extended to demonstrate the robustness of drug adsorption by the disposal system via a desorption study.

Desorption is a phenomenon whereby a substance is released from or through a surface, which in our study is referred to the release of drug from the activated carbon disposal system [21]. The study was designed to simulate a landfill situation where drugs can potentially leach out. High performance liquid chromatography (HPLC) methods used to evaluate the deactivation of opioids were validated to ensure the methods were suitable for their intended use.

## Materials and methods

### Materials

Deterra<sup>®</sup> Drug Deactivation System were provided by Verde Environmental Technologies Inc. (Burnsville, MN). Morphine sulfate, methadone hydrochloride, hydromorphone hydrochloride, and meperidine hydrochloride (active pharmaceutical ingredient) used in this study were purchased from Sigma (St. Louis, MO). Dosage forms used in the study were 20 vials of (multiple dose containers each containing 50 ml) morphine sulfate injections (300 mg/20 ml), two bottles (100 tablets in each bottle) of methadone hydrochloride (10 mg), two bottles (100 tablets in each bottle) of hydromorphone hydrochloride (4 mg), and two bottles (100 tablets in each bottle) of meperidine hydrochloride (10 mg) tablets were provided by Verde Environmental Technologies Inc. (Burnsville, MN). Acetonitrile (ACN), methanol, ammonium acetate, and sodium phosphate monobasic were obtained from Fisher Scientific (Pittsburgh, PA). All other reagents used were of HPLC or American Chemical Society (ACS) grade.

### Methods

#### Chromatographic and detection conditions

An Alliance system (Waters Corporation, Billerica, MA) and reverse-phase HPLC methods were used for the quantification of all samples. HPLC assay methods obtained from previous literature were modified and validated for each drug [22–25]. Morphine was analyzed using a C18 Kinetex (150 × 4.6 mm, 5 μm) column with methanol and pH 4 NH<sub>4</sub>OAc buffer (10:90 v/v) as mobile phase. The flow rate of 1 ml/min with an injection volume of 30 μl and an absorption wavelength of 285 nm was used. For the analysis of methadone, the column used was C18 Kinetex (150 × 4.6 mm, 5 μm) set at 30 °C with acetonitrile (ACN) and water (60:40 v/v) as a mobile phase. A sample volume of 20 μl was injected at a flow rate of 1 ml/min and analyzed at the absorption wavelength of 200 nm. In addition, for the quantitative analyses of hydromorphone and meperidine, the columns used were Kinetex C18 (250 × 4.6 mm, 5 μm) and Kinetex C18 (250 × 3.5 mm, 5 μm) set at 40 °C, respectively. Hydromorphone was analyzed under the influence of mobile phase ACN:water (0.5% w/v sodium dodecyl sulfate and 0.4% trifluoroacetic acid) in a composition ratio of 35:65 (% v/v). Whereas for meperidine, ACN: buffer (0.02 M ammonium acetate, pH 6.9) in a composition ratio of 35:65 (% v/v) was used as the mobile phase. An injection volume of 20 μl at a flow rate of 1 ml/min was used for both hydromorphone and meperidine. The absorption wavelength of hydromorphone was 282 nm and that of meperidine was 258 nm. All standards used for HPLC quantification were prepared in deionized water.

#### Validation of HPLC methods

Method validation provides high degree of assurance and evidence that the method employed for the specific purpose is suitable for its intended use. Considering analytical method validation

can provide consistent, reliable, and accurate results, all the HPLC methods used in this study were validated to demonstrate that the methods employed can guarantee reliable determination levels of the four opioids in the samples. The HPLC methods were validated in terms of specificity, linearity, accuracy, and precision. Method validation of all the four drugs was performed over a 3-d period. The specificity of each assay was determined by comparing the chromatograms of the blank solution (water) with that of the drug standard solution (drug in water) of varying concentrations. Linearity of the standard curves was determined over a range of 2.5–50 µg/ml for morphine, 0.1–50 µg/ml for methadone, and 0.25–100 µg/ml in case of hydromorphone and meperidine. Accuracy of the methods was determined for both intra-day and inter-day variations using multiple analysis of different concentrations of samples. The precision of the methods was determined by repeatability (intra-day), which is performed during the same day, and intermediate precision (inter-day) that was assessed by comparing the assays on three different days.

#### Deactivation of dosage forms

This study was performed as per the protocol established by Verde Technologies Inc. (Minnetonka, MN) in association with the National Institute on Drug Abuse (NIDA) where this unique activated carbon based disposal system was used to evaluate the deactivation efficiency of four model opioid medications. Deactivation studies were done in duplicates, to use the duplicate pouch in case of any spillage during handling of the pouches or accidental rupture of pouch. Deactivation of methadone, meperidine, hydromorphone tablets, and morphine solution was tested using the drug disposal system up to 28 d. The schematic representation is shown in Figure 1 where 20 ml solution of morphine sulfate or 10 tablets of all the other model drugs were stored in the activated carbon containing pouches. About 50 ml of warm tap water (43 °C) was added into the pouches containing methadone, hydromorphone, and meperidine tablets while 30 ml of tap water was added into the pouches containing morphine sulfate solution. The pouches were then sealed after 30 s and agitated to ensure thorough contact of the drugs with the activated carbon. All the pouches were stored upright in a cabinet at room temperature during the study period. Samples were collected at 8 h, 1, 2, 4, 7, 14, 21, and 28 d from duplicate pouches at each time point and analyzed by the validated HPLC methods after filtration with 0.22 µm nylon filters.

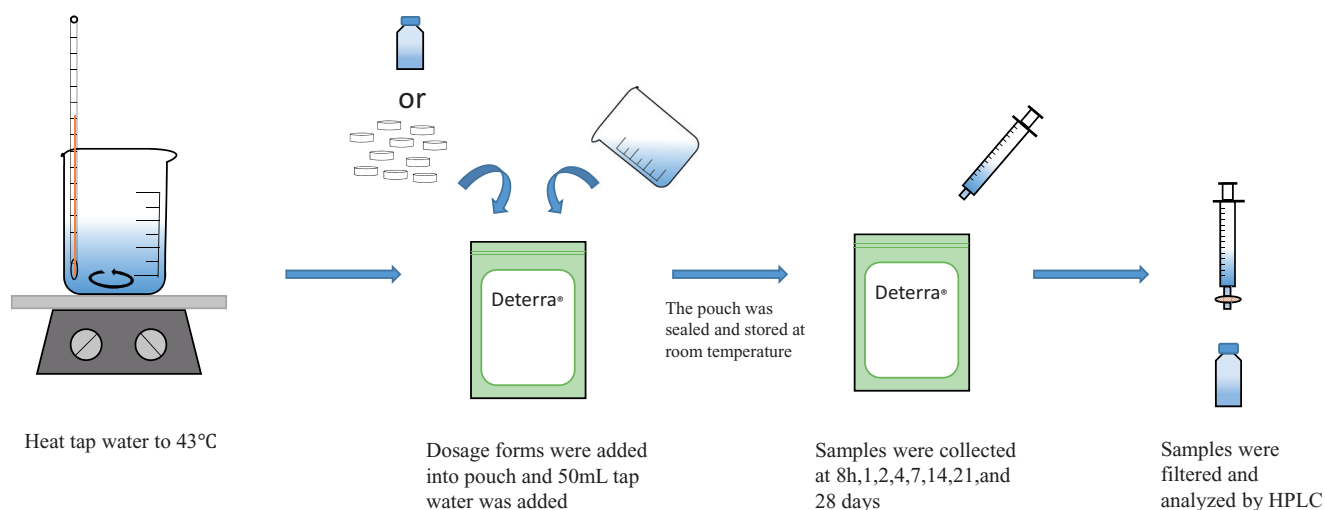


Figure 1. Schematic figure for adsorption study.

#### Desorption study

Desorption studies were done to test the system for potential leaching of the active ingredients from the disposal system in presence of water and alcohol as shown in Figure 2. Landfill situation was simulated by the addition of higher volumes of water and organic solvent to test the potential leaching of drugs from the disposal system into landfill. At the end of the adsorption study, pouch contents of 28 d were transferred to 500 ml closed containers and 200 ml tap water was added into each of these containers. Followed by slow rocking on the platform shaker for 1 h and then allowed to stand for an additional 23 h at room temperature. Samples were taken out, filtered, and analyzed by HPLC followed by complete replacement of the solution in each container with 250 ml of 30% ethanol. After 1 h of shaking and additional 23 h of standing, the samples were filtered and analyzed by HPLC.

## Results

#### Validation of analytical methods

##### Specificity

The analytical methods obtained and modified from the literature enabled the direct determination of the different drugs without any significant interference [26]. Chromatographic peaks of blank solution (a) and standard drug solution (b) of four opioids are represented in Figures 3–6. The drug peaks were well separated from matrix samples indicating the specificity of the analytical methods. Samples generated from adsorption and desorption studies were also compared to blank and standard drug solutions but showed no interfering peaks at the drug retention time.

##### Linearity

Linearity is the ability of the analytical method to elicit results that are directly proportional to the concentration of the analyte within a given range. The acceptance criterion for linearity is that the correlation coefficient ( $r^2$ ) should not be less than 0.990. Standard curve plots of morphine, methadone, hydromorphone, and meperidine for 3 d were found to be linear in the range of 2.5–50, 0.1–50, 0.25–100, and 0.25–100 µg/ml, respectively, with an  $r^2 \geq 0.999$ . The results demonstrated linearity of the methods for all four model drugs over a wide range of concentration.

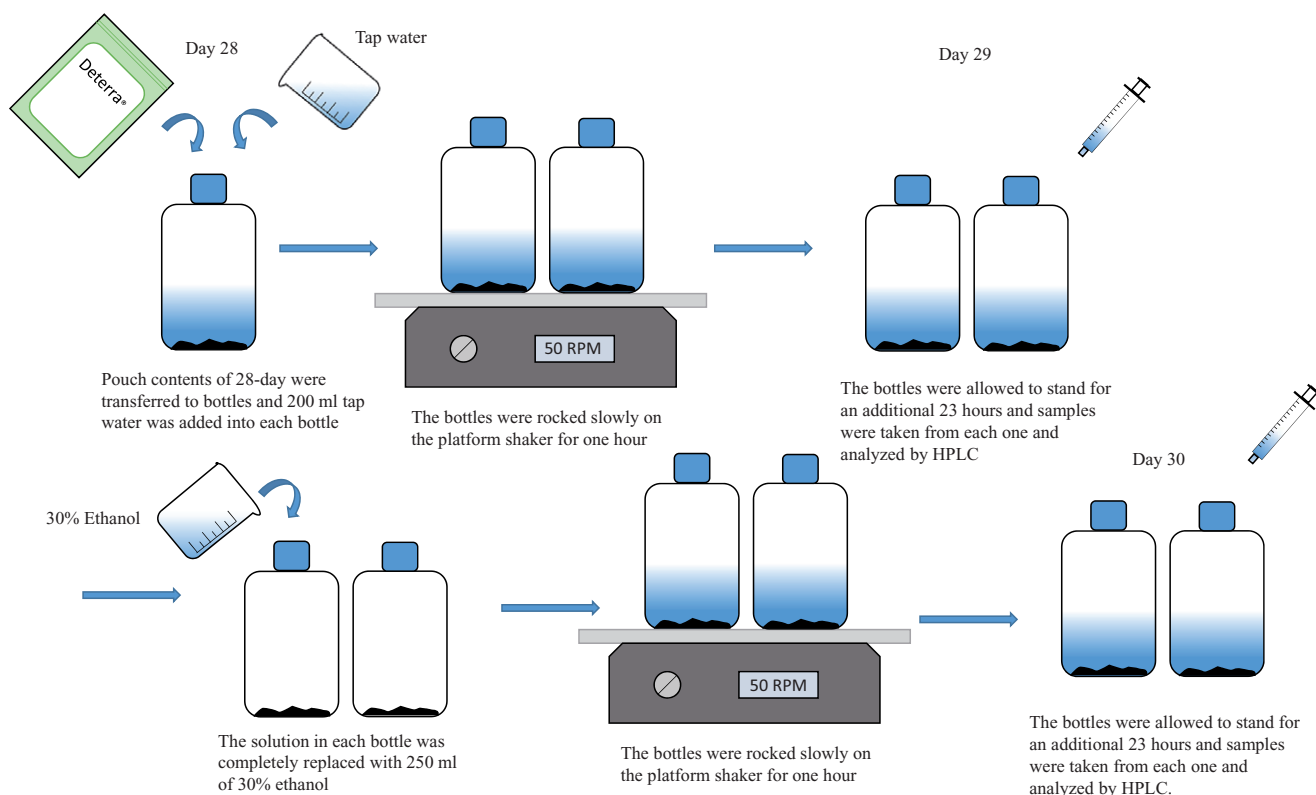


Figure 2. Schematic figure for desorption study.

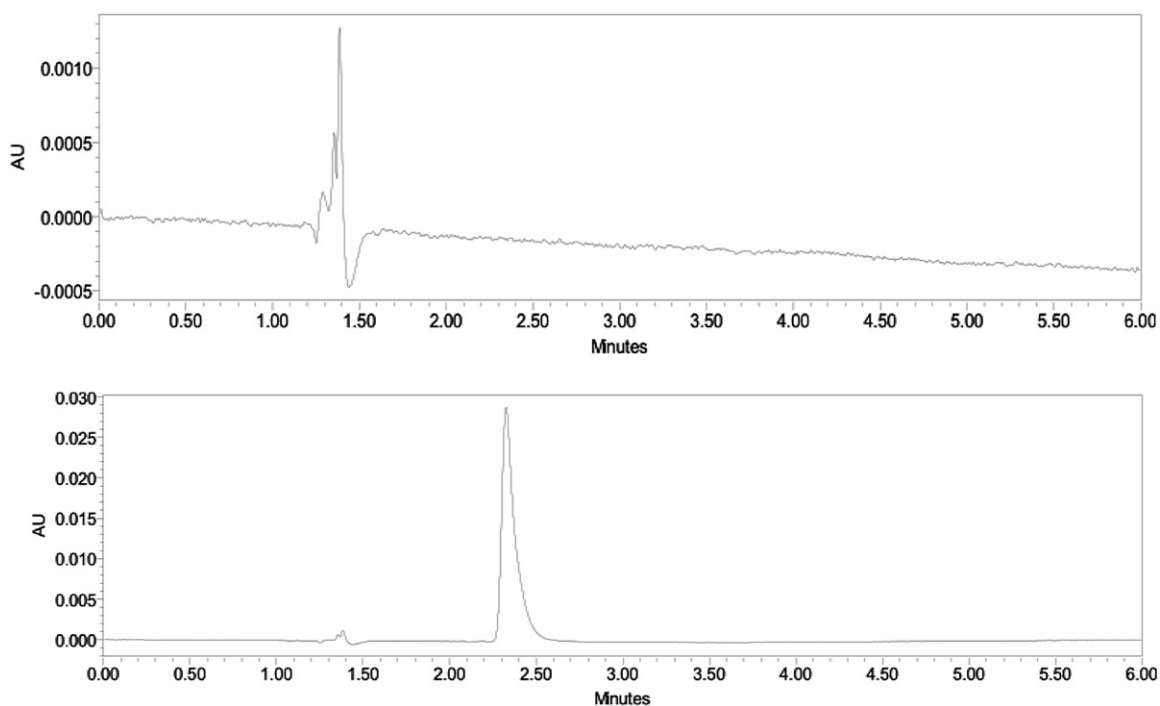


Figure 3. Chromatogram resulting from (a) blank sample, and (b) standard morphine sulfate solution.

#### Accuracy and precision

Accuracy is the closeness of agreement between the reference values with the measured value which is performed at three concentrations within the range of the method. Precision is the measure of the repeatability of the method under normal operation, which represents the closeness of agreement of a series of

measurements from multiple sampling of a same sample. Intra-day and inter-day accuracies and precision for the HPLC methods were tested for the four model drugs and are listed in Table 1. For all drugs tested, the intra-day and inter-day accuracy ranged from a minimum of 91.92% to a maximum of 112.53% and the precision was within 10% as shown in Table 1.

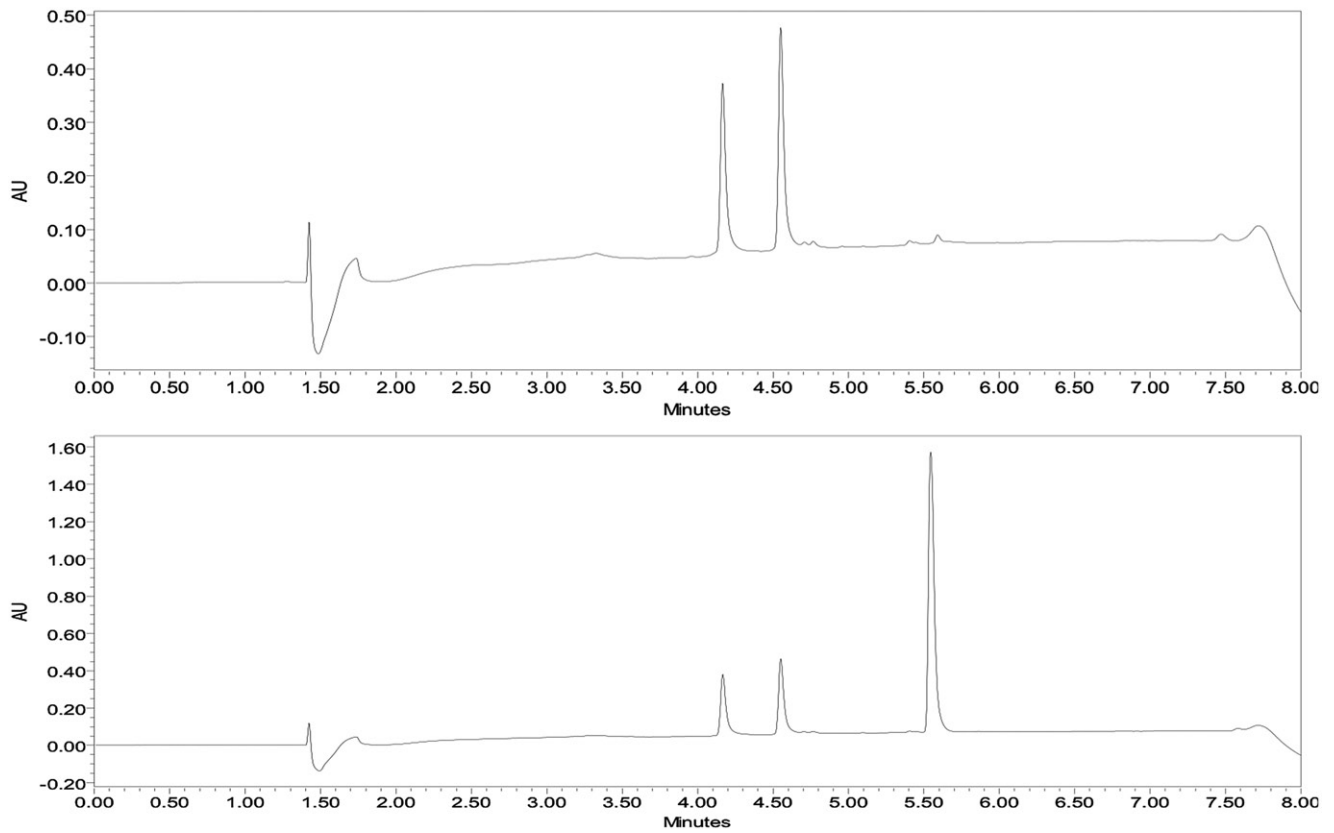


Figure 4. Chromatogram resulting from (a) blank sample, and (b) standard methadone hydrochloride solution.

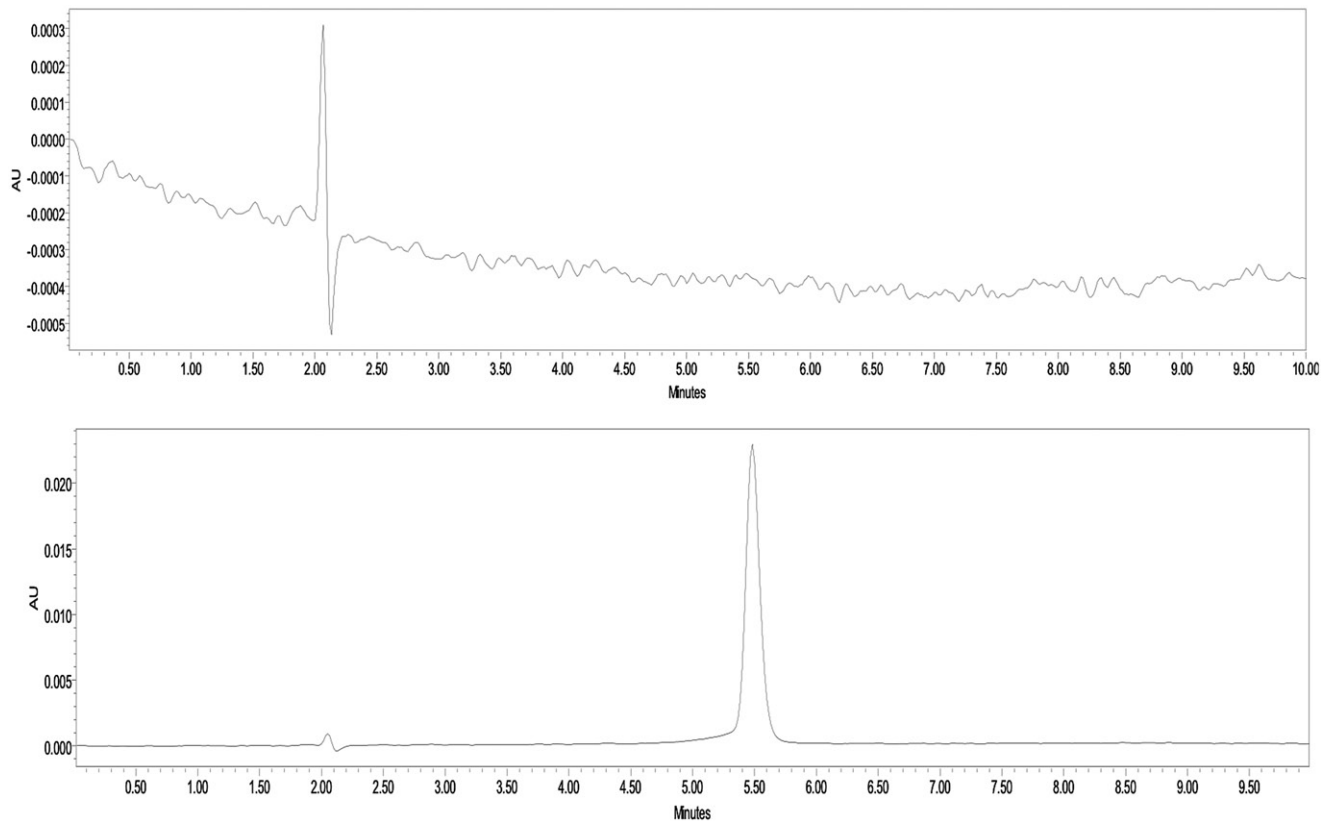


Figure 5. Chromatogram resulting from (a) blank sample and (b) standard hydromorphone hydrochloride solution.

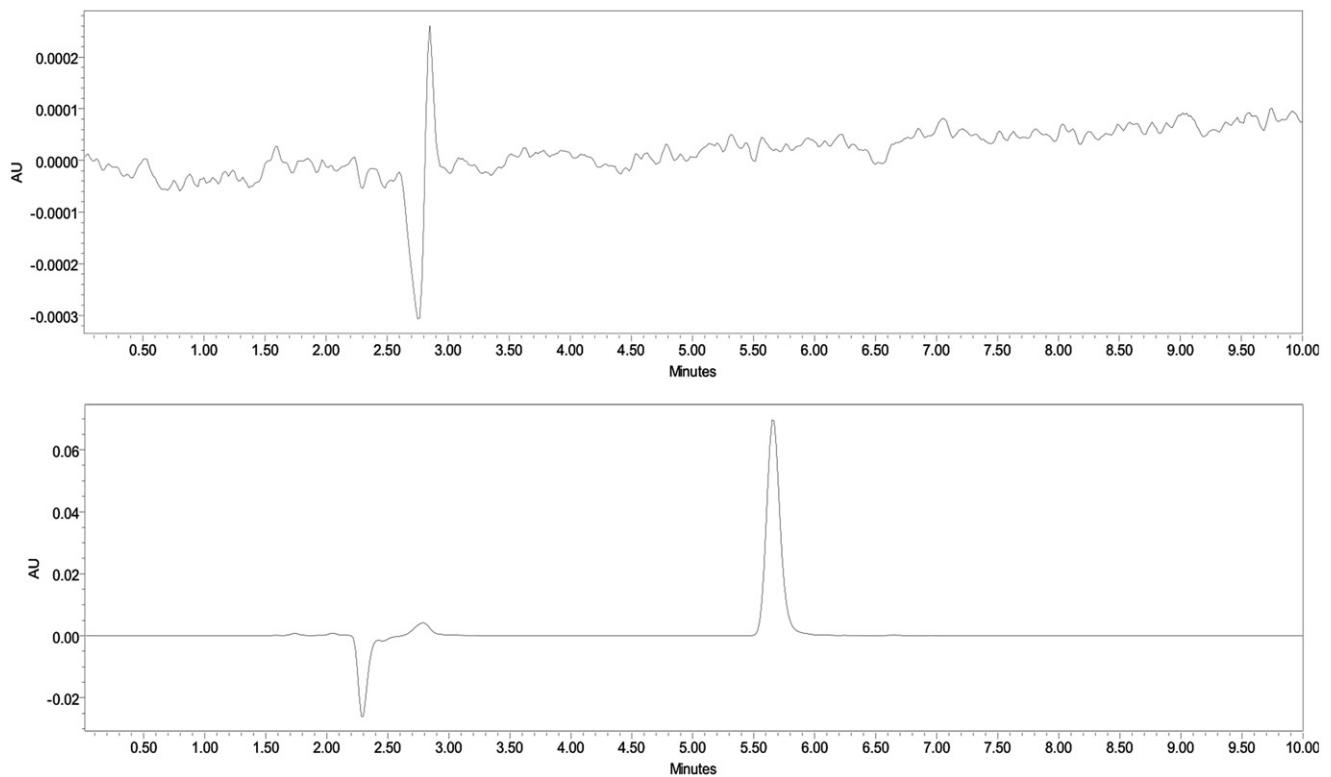


Figure 6. Chromatogram resulting from (a) blank sample and (b) standard meperidine hydrochloride solution.

Table 1. Intra-day and inter-day accuracies and precision of HPLC assay for the four drugs.

Opioids	Reference value ( $\mu\text{g/ml}$ )	Intra-day ( $n = 6$ )			Inter-day ( $n = 3$ )		
		Mean $\pm$ SD	Precision (%)	Accuracy (%)	Mean $\pm$ SD	Precision (%)	Accuracy (%)
Morphine sulfate	2.5	2.34 $\pm$ 0.1	4.99	93.5	2.39 $\pm$ 0.2	6.95	95.7
	10	9.93 $\pm$ 0.2	1.86	99.3	9.95 $\pm$ 0.2	2.14	99.5
	25	25.23 $\pm$ 0.4	1.53	101	25.19 $\pm$ 0.5	1.78	101
Methadone hydrochloride	2.5	2.39 $\pm$ 0.04	1.49	95.7	2.39 $\pm$ 0.05	2.22	95.8
	10	9.31 $\pm$ 0.05	0.54	93.1	9.19 $\pm$ 0.2	2.29	91.9
	25	24.01 $\pm$ 0.4	1.66	96.0	24.12 $\pm$ 0.4	1.63	96.5
Hydromorphone hydrochloride	5	5.14 $\pm$ 0.2	2.98	103	5.27 $\pm$ 0.4	6.79	105
	10	10.49 $\pm$ 0.2	1.50	105	10.19 $\pm$ 0.4	3.91	102
	25	23.20 $\pm$ 0.4	1.52	92.8	24.30 $\pm$ 1.2	5.02	97.2
Meperidine hydrochloride	10	10.81 $\pm$ 0.2	1.56	108	11.25 $\pm$ 0.5	4.71	113
	25	25.55 $\pm$ 0.2	0.71	102	25.62 $\pm$ 0.6	2.20	102
	50	54.77 $\pm$ 0.4	0.80	110	50.36 $\pm$ 5	9.17	101

### Deactivation study

Deactivation of the four opioid model drugs (morphine, methadone, hydromorphone, and meperidine) with the drug disposal system was observed over 28 d. Once the dosage forms were placed into the pouches and water was added, adsorption starts almost immediately. For morphine and hydromorphone, almost all of the drug (99.84% and 100%) were adsorbed while in case of methadone and meperidine, 97.12% and 97.93% of the drugs were deactivated by the drug disposal system by the end of 8 h. All four opioids continued to be adsorbed over time and by the end of 28 d, an average of  $99.99 \pm 0.01\%$  of the drugs were effectively deactivated by the drug disposal system. The deactivation profile of all the four opioids is presented in Figure 7.

### Desorption study

Desorption study was performed in order to test the potential desorption of the opioids from activated carbon after exposed to

a landfill situation by adding higher volumes of water and organic solvent. At the end of the 28-d adsorption study, all the pouch contents were transferred to the containers and 200 ml of tap water was added into each container. Almost no drug leached out after one day of desorption (Table 2). To test the robustness of the system to extraction by alcohol, the solution in the container was replaced by the same volume (250 ml) of 30% alcohol. Due to the strong interaction of the drug molecules with the activated carbon, an average of less than 1.3% of drugs leached out from activated carbon after 24 h (Figure 8).

### Discussion

Prescription opioid medications have been widely used in pain management for many decades. Although opioid therapy is successful in relieving pain, it is associated with risks for misuse and abuse. The high risk of intentional abuse for non-medical purposes is due to the euphoric effects produced by these opioids or may



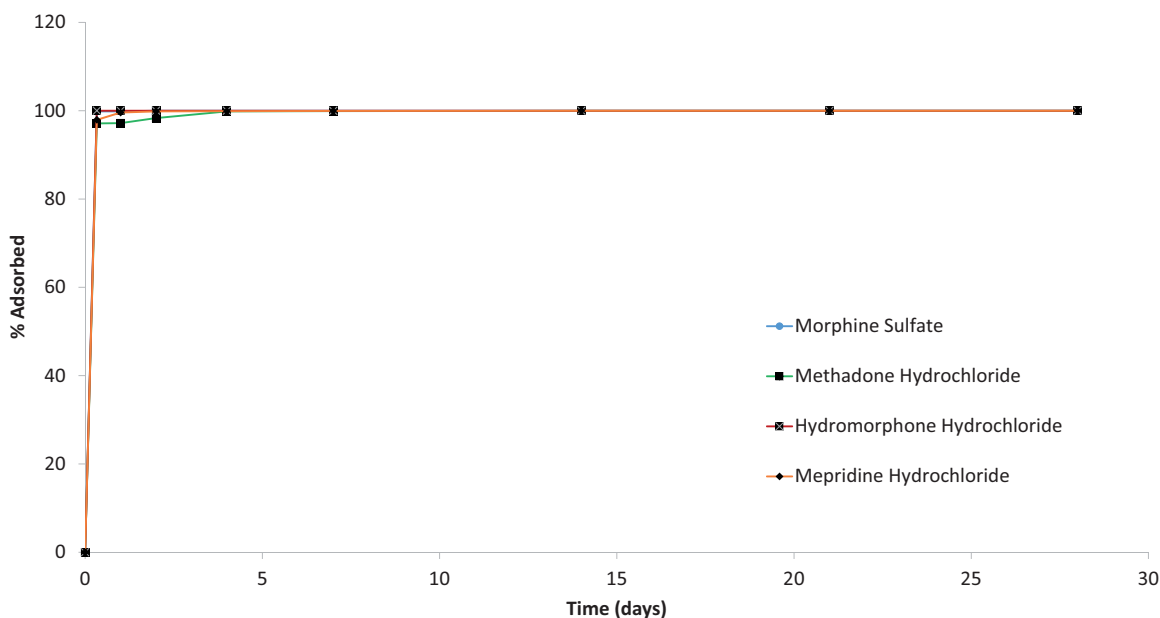


Figure 7. Deactivation profiles of four opioid drugs.

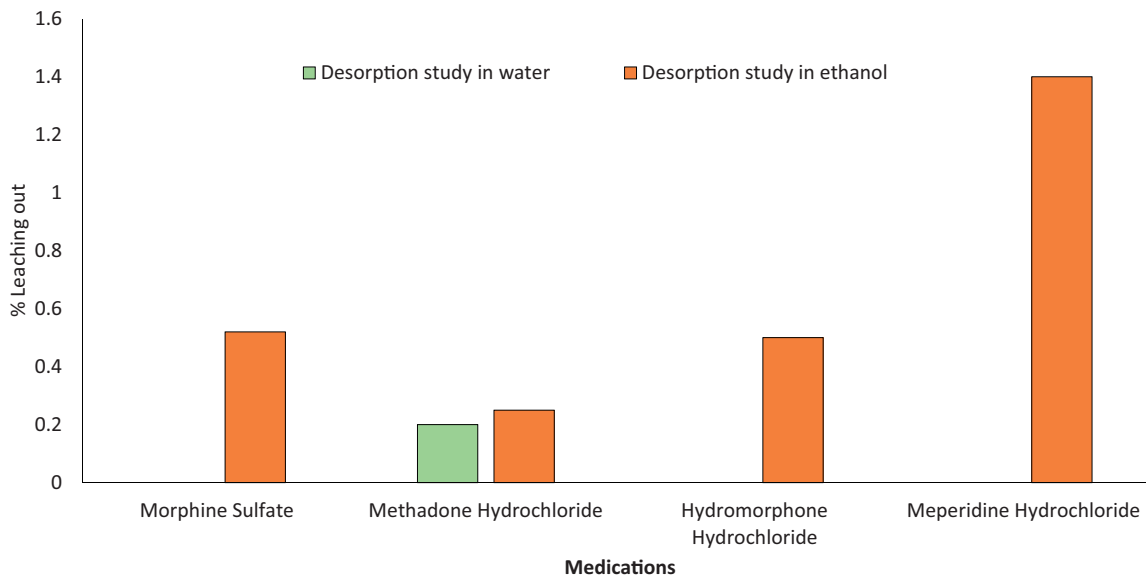
Table 2. Desorption study of morphine, methadone, hydromorphone, and meperidine in water and ethanol.

Medications	% Leached in water	% Leached in ethanol
Morphine sulfate	0.00	0.52
Methadone hydrochloride	0.20	0.25
Hydromorphone hydrochloride	0.00	0.50
Meperidine hydrochloride	0.00	1.40

be due to a greater degree of drug dependence associated with such drugs and in order to avoid withdrawal symptoms. Unsafe storage conditions and hesitancy to dispose these medications after its prescribed use is one of the reasons which may lead to the abuse and diversion of leftover drugs. In addition, direct disposal of these medications in household trash is imprudent and is a major cause of abuse or accidental exposure by children [27–29]. Hence, the proper use, storage, and disposal of opioid analgesics have been identified as one feasible step to counteract such illegal and harmful activities. If take-back programs or other similar alternatives are not readily available or if individuals are not aware of such programs, flushing medications down sewer drains is a common recommendation made to consumers. In fact, toilet disposal has the lowest emissions and is regarded as the fastest and easiest way to dispose controlled substances [30]. However, many sewage treatment plants are ill-equipped to handle such compounds in wastewater due to which these compounds have been detected even in surface and tap water. As a result, many environmentalists consider this method to be the least desirable largely due to the unknown effects on the environment [31]. Although incineration following proper disposal of these controlled substances is regarded as the most environmental friendly way, studies show that airborne emissions of carcinogens, global warming, and ozone depleting compounds increases significantly on incinerating pharmaceuticals [30]. Due to this, compromises are required to maintain a proper balance between human and environmental exposure resulting in consequences such as accidental poisoning, unintended overdoses, prescription drug misuse, and pharmaceutical waste.

The drug disposal system investigated in our study provides a simple and sustainable way to combat these problems and comply with the federal regulations at the same time. A key component of this disposal system is proprietary activated carbon contained

within a pouch, which has a very small particle size and a large surface area [32]. In many studies, activated carbon has been recommended for treating different drug overdose or chemical poisonings in emergency situations due to its strong adsorption property [33]. Adsorption is a phenomenon which occurs when an adsorbate adheres to the surface of an adsorbent, such as activated carbon, due to hydrophobic and electrostatic interactions between the two [34]. Activated carbon is a universal adsorbent, which can inactivate drug substances by adherence of an extremely thin layer of the compounds to the surface of the carbon by Van Der Waals forces and other stronger bonds. Adsorption efficiency of activated carbon is contributed mainly by the presence of micro-pores which provides the maximum surface area from 500 to 1500 g/m<sup>2</sup> and causes sufficient adsorption and retention of pharmaceutical compounds [35]. With adsorption, the intermolecular force which connects the carbon and the drug substances may strongly prevent the release of the molecules from the carbon and render the drug substances physiologically inactive. The adsorption efficiency is also influenced by the structure of the drug molecules or adsorbate [36]. The presence of aromatic rings in all of the four opioid drugs contributes to their hydrophobicity and adsorption by activated carbon due to pi–pi interactions [37]. Morphine sulfate solution provided greater surface area since the drug was in a pre-dissolved state, this lead to faster adsorption to activated carbon compared with adsorption of drugs in solid dosage form. Solid dosage forms like tablets require dissolution of the drugs in water before adsorption can occur. Dissolution to precede adsorption can slightly delay the rate of adsorption of methadone tablets compared to morphine solution. Previous research has noted the influence of molecular weight and hydrophobicity of the adsorbate on adsorption capacity of activated carbon. In our study, we did not observe any significant differences in the adsorption capacity of the disposal system towards the model opioids. The results from our adsorption studies revealed the robustness of the drug disposal system by demonstrating 99.98–100% deactivation of all the opioid medications. Within 8 h, more than 98% of the drug substances had been adsorbed to the activated carbon. The minor difference (2.88–0.01%) in the deactivation profile of the drugs is due to the variation in HPLC method linearity. As presented in the method



**Figure 8.** Desorption study of four opioids with 30% ethanol and water.

validation, linearity of the drugs varied from 2.5–50, 0.1–50, 0.25–100, and 0.25–100 for morphine, methadone, hydromorphone, and meperidine, respectively. From the range of linearity, it is evident that the sensitivity of the HPLC methods for the opioids differed and this difference is the reason we see a minor difference in the deactivation profiles of the drugs. The recommended capacity for this disposal system is 15 pills, 2 ounces of solution or two transdermal patches per pouch. Hence, the formulation used to test the drug disposal system did not exceed the limit.

Active pharmaceutical ingredients (APIs) released into the environment via improper disposal such as landfill leaching may contaminate freshwater resources [11]. To examine the robustness of the drug disposal system in retaining the adsorbed pharmaceuticals, a desorption study was carried out with large quantities of water and organic solvent under agitation conditions where there is a strong likelihood of the drug leaching out of carbon. The aqueous washout test showed that the medications remained highly adsorbed to the activated carbon and thus cannot leach out to cause contamination of the environment in presence of large volumes of water. On extraction with alcohol, less than 1.3% of the drugs leached out of the system indicating that most of the drug has already been deactivated by adsorption to activated carbon and the risk of leaking of these drugs from landfills may be eliminated. Hydrophobicity of the opioids influenced their leaching out from alcohol during the desorption study. A previous investigation by Nam et al. established the influence of hydrophobicity with adsorption efficiency of activated carbon [26]. Methadone has the highest hydrophobicity with the largest partition coefficient compared with the other three opioids and thus showed the lowest extraction from alcohol due to the strongest binding with activated carbon.

## Conclusion

In conclusion, the improper disposal of prescription opioids is a major concern due to associated potential abuse and risks of environmental contamination. Despite existing disposal protocols and programs, there is an imperative need for an environmentally safe, convenient, and effective drug disposal system. The disposal system evaluated in our study furnishes this need by demonstrating its efficiency by deactivating and retaining the four model

opioids with high abuse potential. This system could successfully adsorb or deactivate 99.99% of the four model opioids within 28 d and did not release them when exposed to different stress conditions. Hence, this drug disposal system is not only an improvement over traditional methods of disposal of unused medications at home but also furnishes the need for a simple, convenient, safe, and environmentally friendly drug disposal procedure for both patients and healthcare providers. While our study demonstrates a promising drug disposal system, further testing with a range of drugs and dosage forms is required to deem the disposal system universal.

## Disclosure statement

The authors report no conflicts of interest.

## Funding

The current research project was funded by Verde Technologies (Minnetonka, MN) as a SBIR Phase II contract from National Institute on Drug Abuse (NIDA). Title: In-Home Deactivation System for Psychoactive Drugs (SBIR Phase 2), Contract no. HHSN271201400068C NIDA Reference no. N44DA-14-4420.

## References

- [1] What is the scope of prescription drug misuse? [Internet]. National Institute on Drug Abuse (NIDA); 2016 [cited 2016 Nov 26]; Available from: <https://www.drugabuse.gov/publications/research-reports/misuse-prescription-drugs/what-scope-prescription-drug-misuse>
- [2] Opioid painkiller prescribing, where you live makes a difference [Internet]. Centers for Disease Control and Prevention; 2014; [cited 2016 Nov 26]; Available from: <http://www.cdc.gov/vitalsigns/opioid-prescribing/>
- [3] Akil H, Watson SJ, Young E, et al. Endogenous opioids: biology and function. *Annu Rev Neurosci.* 1984;7:223–255.
- [4] Kosten TR, George TP. The neurobiology of opioid dependence: implications for treatment. *Sci Pract Perspect.* 2002;1:13–20.

- [5] Prescription opioid overdose data [Internet]. Centers for Disease Control and Prevention; 2016 [cited 2016 Dec 20]; Available from: <https://www.cdc.gov/drugoverdose/data/overdose.html>
- [6] Overdose death rates [Internet]. National Institute on Drug Abuse (NIDA); 2017 [cited 2017 Feb 5]; Available from: <https://www.drugabuse.gov/related-topics/trends-statistics/overdose-death-rates>
- [7] Substance Abuse and Mental Health Services Administration. Results from the 2011 National Survey on Drug Use and Health: Summary of National Findings, 2012. Rockville, MD: Substance Abuse and Mental Health Services Administration; 2012. NSDUH Series H-41; HHS publication (SMA) 11-4658.
- [8] How to dispose of unused medicines [Internet]. U.S. Food and Drug Administration (FDA); 2015 [cited 2016 Oct 5]; Available from: <http://www.fda.gov/ForConsumers/ConsumerUpdates/ucm101653.htm>
- [9] Kasprzyk-Hordern B, Dinsdale RM, Guwy AJ. The occurrence of pharmaceuticals, personal care products, endocrine disruptors and illicit drugs in surface water in South Wales, UK. *Water Res.* 2008;42:3498–3518.
- [10] Medicine disposal: questions and answers [Internet]. U.S. Food and Drug Administration (FDA); 2016 [cited 2016 Oct 8]; Available from: <http://www.fda.gov/Drugs/ResourcesForYou/Consumers/BuyingUsingMedicineSafely/EnsuringSafeUseofMedicine/SafeDisposalofMedicines/ucm186188.htm>
- [11] Daughton CG, Ruhoy IS. Environmental footprint of pharmaceuticals: the significance of factors beyond direct excretion to sewers. *Environ Toxicol Chem.* 2009;28:2495–2521.
- [12] Bueno MJM, Gomez MJ, Herrera S, et al. Occurrence and persistence of organic emerging contaminants and priority pollutants in five sewage treatment plants of Spain: two years pilot survey monitoring. *Environ Pollut Barking Essex* 1987. 2012;164:267–273.
- [13] Safe disposal of unused controlled substances report [Internet]. [cited 2016 Oct 21]; Available from: <http://www.ncdoi.com/osfm/safekids/Documents/OMD/SafeDisposalOfUnusedControlledSubstancesReport.pdf>
- [14] Dosed without prescription: preventing pharmaceutical contamination of our nation's drinking water [Internet]. NRDC white paper; 2009 [cited 2016 Nov 1]; Available from: [https://www.nrdc.org/sites/default/files/hea\\_10012001a.pdf](https://www.nrdc.org/sites/default/files/hea_10012001a.pdf)
- [15] Waybright VB, Ma SH, Schug KA. Validated multi-drug determination using liquid chromatography with tandem mass spectrometry for the evaluation of a commercial drug disposal product. *J Sep Sci.* 2016;39:1666–1674.
- [16] Medsaway™ system deactivation of unused drugs: comparison between Medsaway ingredients and others recommended in federal and SmartRx disposal guidelines [Internet]. 2012 [cited 2016 Nov 22]; Available from: <http://deterrasystem.com/wp-content/uploads/2015/05/Fowler-White-Paper-10-8-12.pdf>
- [17] Types of opioids [Internet]. Opiate addiction and treatment resource; 2013 [cited 2016 Nov 20]; Available from: [http://www.opiateaddictionresource.com/opiates/types\\_of\\_opioids](http://www.opiateaddictionresource.com/opiates/types_of_opioids)
- [18] Hydromorphone abuse causes, statistics, addiction signs, symptoms and side effects [Internet]. Addiction Hope; 2013 [cited 2016 Dec 25]; Available from: <https://www.addiction-hope.com/hydromorphone/>
- [19] Meperidine – FDA prescribing information, side effects and uses [Internet]. 2016 [cited 2016 Dec 25]. Available from: <https://www.drugs.com/pro/meperidine.html>
- [20] Bohnert ASB, Ilgen MA, Trafton JA, et al. Trends and regional variation in opioid overdose mortality among Veterans Health Administration patients, fiscal year 2001 to 2009. *Clin J Pain.* 2014;30:605–612.
- [21] What's the difference between absorption and adsorption and sorption [Internet]. [cited 2016 Oct 21]; Available from: <https://interdry.wordpress.com/2010/09/22/what-the-difference-between-absorption-and-adsorption-and-sorption/>
- [22] Ruzilawati AB, Wan Yusuf WN, Ramli N, et al. Determination of morphine in human urine by a simple reverse phase high-performance liquid chromatography method with UV detection. *Int J Pharm Sci Drug Res.* 2013;5:18.
- [23] LC/MS/MS analysis of methadone from urine using Strata-X-Drug B on a Kinetex C18 2.6µm, 50x2.1mm [Internet]. [cited 2016 Oct 21]; Phenomenex. Available from: <http://www.phenomenex.com/Application/Detail/19703>
- [24] Smet E, Weken GV, der Baeyens WRG, et al. A validated HPLC method for assay of morphine hydrochloride and hydromorphone hydrochloride in pharmaceutical injections. *Chromatographia.* 2001;53:35–39.
- [25] Das Gupta V. Quantitation of meperidine hydrochloride in pharmaceutical dosage forms by high-performance liquid chromatography. *J Pharm Sci.* 1983;72:695–697.
- [26] Validation of analytical procedures, text and methodology Q2(R1). [Internet]. International Conference on Harmonisation of Technical Requirements for Registration of Pharmaceuticals for Human Use (ICH); 2005 [cited 2016 Oct 23]; Available from: [https://www.ich.org/fileadmin/Public\\_Web\\_Site/ICH\\_Products/Guidelines/Quality/Q2\\_R1/Step4/Q2\\_R1\\_Guideline.pdf](https://www.ich.org/fileadmin/Public_Web_Site/ICH_Products/Guidelines/Quality/Q2_R1/Step4/Q2_R1_Guideline.pdf)
- [27] Bronstein AC, Spyker DA, Cantilena LR, et al. 2007 Annual Report of the American Association of Poison Control Centers' National Poison Data System (NPDS): 25th Annual Report. *Clin Toxicol Phila, PA.* 2008;46:927–1057.
- [28] McFee RB, Caraccio TR. "Hang Up Your Pocketbook – an easy intervention for the granny syndrome: grandparents as a risk factor in unintentional pediatric exposures to pharmaceuticals". *J Am Osteopath Assoc.* 2006;106:405–411.
- [29] Armstrong EJ, Jenkins AJ, Sebrosky GF, et al. An unusual fatality in a child due to oxycodone. *Am J Forensic Med Pathol.* 2004;25:338–341.
- [30] Cook SM, VanDuijn BJ, Love NG, et al. Life cycle comparison of environmental emissions from three disposal options for unused pharmaceuticals. *Environ Sci Technol.* 2012;46:5535–5541.
- [31] Pharmaceuticals and personal care products (PPCPs) as environmental pollutants: pollution from personal actions [Internet]. United States Environmental Protection Agency (EPA); 2004 [cited 2016 Dec 26]; Available from: [https://cfpub.epa.gov/si/si\\_public\\_record\\_report.cfm?dirEntryId=76663](https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=76663)
- [32] Balaney JAG, Crawford SA, Lungu CT. Comparison of toluene adsorption among granular activated carbon and different types of activated carbon fibers (ACFs). *J Occup Environ Hyg.* 2011;8:573–579.
- [33] Thakore S, Murphy N. The potential role of prehospital administration of activated charcoal. *Emerg Med J.* 2002;19:63–65.
- [34] Nam SW, Choi DJ, Kim SK, et al. Adsorption characteristics of selected hydrophilic and hydrophobic micropollutants in water using activated carbon. *J Hazard Mater.* 2014;270:144–152.
- [35] Dubinin MM. Fundamentals of the theory of adsorption in micropores of carbon adsorbents: characteristics of their

- adsorption properties and microporous structures. *Carbon*. 1989;27:457–467.
- [36] Herwadkar A, Singh N, Anderson C, et al. Development of disposal systems for deactivation of unused/residual/expired medications. *Pharm Res*. 2016;33:110–124.
- [37] Bäuerlein PS, Mansell JE, Ter Laak TL, et al. Sorption behavior of charged and neutral polar organic compounds on solid phase extraction materials: which functional group governs sorption? *Environ Sci Technol*. 2012;46:954–961.