Electrochemical strategies for adulterated heroin samples

Electrochemical Strategies For Adulterated Heroin Samples

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ABSTRACT: *Electrochemical strategies to selectively detect heroin in street samples without the use of complicated electrode modifications were developed for the first time. For this purpose, heroin, mixing agents (adulterants, cutting agent and impurities) and their binary mixtures were subjected to square wave voltammetry measurements at bare graphite electrodes at pH 7.0 and pH 12.0, in order to elucidate the unique electrochemical fingerprint of heroin and mixing agents as well as possible interferences or reciprocal influences. Adjusting the pH from pH 7.0 to pH 12.0 allowed a more accurate detection of heroin in the presence of most common mixing agents. Furthermore, the benefit of introducing a preconditioning step prior to running square wave voltammetry on the electrochemical fingerprint enrichment was explored. Mixtures of heroin with other drugs (cocaine, 3,4-methylenedioxymethamphetamine and morphine) were also tested to explore the possibility of their discrimination and simultaneous detection. The feasibility of the proposed electrochemical strategies was tested on realistic heroin street samples from forensic cases, showing promising results for fast, on-site detection tools of drugs of abuse.*

Keywords: heroin, illicit drugs, electrochemistry, square wave voltammetry

The widespread use of illicit drugs and the consequences of drug abuse on individuals and societies has led to increasing efforts to quickly and accurately detect drugs on-the-site.

Electrochemical methods proved to be excellent techniques for the fast determination of drugs with high sensitivity and specificity, suitable for the development of miniaturized portable devices to be used in-field. Electrochemical detection of several illicit drugs (identification based on the voltammetric oxidation potential) has been reported in literature, and proved to be effective for accurately detecting illicit drugs in complex adulterated samples [1, 2, 3]. For example, a portable sensor for cocaine and adulterants determination was described by Richter's group based on square wave voltammetry measurements on boron doped diamond electrodes coupled with a batch injection system [4]. Our group developed a wearable fingerprint sensor for quick on-site screening of cocaine and cutting agents [5] and demonstrated the superior accuracy of electrochemical methods to color tests for cocaine detection [6]. Direct voltammetric analysis on unmodified electrodes of a number of other drugs of abuse in street samples was also recently reported in literature [2].

Heroin (3,6-diacetylmorphine, diamorphine) is a highly addictive opiate drug synthesized by acetylation of morphine, a naturally occurring compound in poppy seeds. Heroin has the second largest share of EU drug retail market (28%) after cannabis (38%) and is the most common and rapidly acting opioid on the EU market [7]. Heroin is rarely sold on the streets in its pure form, as a white powder. As the drug is usually mixed with other compounds, the purity of heroin can vary widely making it difficult to evaluate the strength of the dose and leading to an increased incidence of fatal overdose [8, 9]. The purity of heroin varies between 11% and 40% in the EU with an average of 15-29% (the differences varying across countries) [7]. Therefore, the color of illicit heroin varies from white, beige to medium and dark brown due to impurities formed during the manufacturing process or adulterants and cutting agents. As the drug is usually mixed with other compounds, the purity of heroin can vary widely making it difficult to evaluate the strength of the dose and leading to an increased incidence of fatal overdose [8, 9]. The purity of heroin varies between 11% and 40% in the EU with an average of 15-29% (the differences varying across countries) [7]. Impurities commonly present in heroin samples include opium alkaloids or by-products from the fabrication process, such as morphine, monoacetylmorphine, codeine, acetylcodeine, noscapine, papaverine or lead [10, 11]. The drug can also be mixed with cutting agents (pharmacologically inactive, readily available substances used to dilute the sample) such as starch or sugars, or adulterants (pharmacologically active, less available and more expensive substances) such as paracetamol, caffeine, phenobarbital, quinine, clenbuterol, procaine or levamisole [10-16]. Among the latter paracetamol and caffeine are identified in over 90% of the heroin samples in Europe. Paracetamol mimics the analgesic effect of heroin and caffeine vaporizes heroin at lower temperature facilitating its smoking [16]. Identifying the composition of drug seizures is important from a forensic point of view to track back the source of the supply and trace illicit networks, as well as for the consequences on health that some of the adulterants have.

The electrochemical analysis of heroin was reported only in a few papers. Rodriguez et al studied the electrochemical behavior and oxidation mechanism of heroin on carbon paste electrodes [17]. The voltammetric oxidation of heroin and its metabolites was investigated on glassy carbon electrodes by Garrido et al and a different mechanism of oxidation was proposed [18]. More recently, the simultaneous detection of heroin, morphine and noscapine was studied on glassy carbon electrodes modified graphene nanosheets. The proposed approach allowed to detect the three opiates simultaneously or separately at micromolar concentration without any pretreatment steps or the use of any specific redox mediator [19]. The determination of heroin in street samples in presence of various adulterants and cutting agents has not been reported before.

This work presents for the first time electrochemical strategies for selective detection of heroin in street samples containing various adulterants, cutting agents and impurities without the use of complicated electrode modifications. In our previous work we presented electrochemical strategies for selective detection of cocaine in the presence of the most common adulterants and cutting agents in cocaine samples, elucidating their electrochemical fingerprint. Square wave voltammetry (SWV) was used for extensive screening of cocaine and adulterants at pH 7.0, revealing valuable information on which adulterants pose difficulties in cocaine detection leading to false positive or false negative results by peak suppres-

sion or overlap [6]. Strategies to overcome peak suppression or overlap by adjusting the pH to 12 or introducing a preconditioning step have been proposed [6, 20]. Herein we extent the screening towards heroin to pave the way for a single device able to simultaneously detect a range of illicit drugs in complex samples. For this purpose, heroin, mixing agents (adulterants, cutting agent and impurities) and their binary mixtures were subjected to SWV measurements at pH 7.0 and pH 12.0 on unmodified electrodes. The benefit of introducing a preconditioning step prior to running SWV on the electrochemical fingerprint enrichment was also explored. The feasibility of the proposed strategies was tested on real street heroin samples from forensic cases.

Experimental

Reagents and Samples

Heroin, noscapine, papaverine, caffeine, dextromethorphan, codeine, quinine and procaine were provided by the National Institute of Criminalistics and Criminology (NICC) of Belgium. Levamisole hydrochloride was purchased from Acros Organics (Geel, Belgium). Morphine hydrochloride, scopolamine, clenbuterol, lead nitrate, paracetamol, potassium monophosphate, potassium chloride and potassium hydroxide were purchased from Sigma-Aldrich (Overijse, Belgium).

Seized street samples were provided by the National Institute of Criminalistics and Criminology (NICC) of Belgium. The street samples were analyzed qualitatively and quantitatively by gas chromatography-mass spectrometry (GC-MS) and gas chromatography-flame ionization detection (GC-FID), by NICC in order to establish their chemical composition. The applied chromatographic methods are ISO17025 accredited and are continuously evaluated through participation to international quality control programmes (UNODC, ENFSI, NMI).

Phosphate buffer 20 mM containing 100 mM KCl (PBS) was used as supporting electrolyte for electrochemical measurements and the pH was adjusted to desired value using a 100 mM KOH solution using a CyberScan 510 pH-meter from Eutech Instruments (Landsmeer, The Netherlands) connected to a HI-1131 glass bodied pH electrode from Hanna Instruments (Bedfordshire, United Kingdom). All aqueous solutions were prepared using MilliQ water (R > 18 MΩcm). The reagents were of analytical grade and used without supplementary purification.

Instrumentation and apparatus

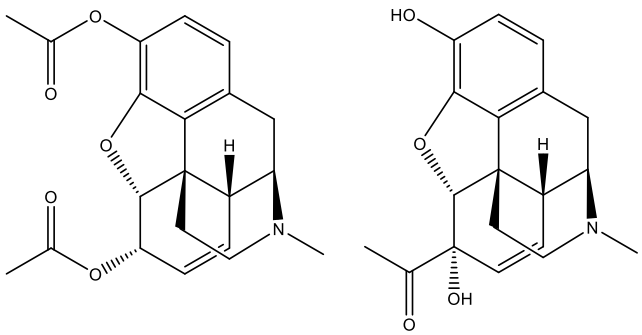
SWV measurements were performed using an Autolab potentiostat/galvanostat (PGSTAT 302N, ECOCHEMIE, The Netherlands) controlled by NOVA software. ItalSens graphite screen-printed electrodes (GSPE) containing a graphite working electrode (3 mm diameter), a carbon counter electrode and a (pseudo) silver reference electrode (PalmSens, The Netherlands) were used for the measurements. SWV measurements were performed by placing 50 µL solution onto the GSPE. All solutions were freshly prepared before running the measurements. For measurements at pH 12.0, solutions were prepared by dilution from stock solutions right before the measurement and the SWV scan was performed within 1 min to avoid variations of the signals due to different hydrolysis times. The single scan SWV parameters were as follows: potential range 0 V to 1.2 V, step potential 5 mV, amplitude 25 mV and frequency 10 Hz. For the preconditioning step a potential of -0.8 V was applied for 180 s prior to running the SWV. All results obtained by SWV were presented after baseline correction using the mathematical algorithm "moving average" (peak width = 1) contained within NOVA software.

On-site measurements were performed using a portable potentiostat EmStat Blue from Palmsens (the Netherlands) connected to a tablet via Bluetooth. The potentiostat was controlled by PStouch software designed for tablets and phones.

Results and Discussion

Electrochemical behavior of heroin on GSPE

Firstly, the electrochemical behavior of heroin (structure shown in Figure 1) on GSPE was studied to establish its specific electrochemical fingerprint. To assess a possible enrichment of the fingerprint by changing the pH, and since it was previously demonstrated that heroin's half-peak potential is strongly influenced by pH [17, 18, 21], the pH of the electrolyte solution was varied between 2 and 12. The previous pH studies were done by differential pulse voltammetry on carbon paste electrodes [17, 21] and glassy carbon electrodes [17]. We investigated the pH dependency on heroin oxidation peak on GSPE.



Heroin 6-monoacetylmorphine

Figure 1. Chemical structure of heroin and of its hydrolysis product and metabolite, 6-monoacetylmorphine (6-MAM).

As seen in Figure 2, at pH 7.0 on GSPE, heroin gives rise to an irreversible oxidation peak at 0.81±0.02 V on GSPE due to the oxidation of the amine group, which is in good agreement with previously reported data [17-19, 21]. An additional oxidation peak was observed at a lower potential (0.40±0.02 V) due to the oxidation of the phenol group of 6-MAM (structure shown in Figure 1) present in the sample, in 3 wt%. 6-MAM is an intermediate product in heroin synthesis, resulting from incomplete acetylation of morphine, and a product of hydrolysis of heroin [22] and is thus present in most heroin samples. 6-MAM also occurs as an active metabolite of heroin and points to very recent heroin consumption when detected in urine or blood [23]. A study of 383 heroin samples seized in Denmark showed the presence of 6-MAM in all samples. The same study showed that storage of illicit heroin resulted in a decrease of the concentration of heroin and an increase in the concentration of 6-MAM, due to spontaneous deacetylation of heroin [22]. Thus the oxidation peak of 6-MAM at 0.40±0.02 V can be included as part of the electrochemical fingerprint of heroin. Hence one can state that the electrochemical fingerprint of illicit heroin at GSPE in PBS pH 7.0 consists of two oxidation peaks at 0.81±0.02 V (peak 1) and

0.40±0.02 V (peak 2). As the pH increases from pH 3.0 to pH 12.0 both peaks shift to more negative potentials. Only one peak is observed at pH 3 (peak 2), while at pH 12.0 the intensity of peak 2 substantially increases due to fast hydrolysis of heroin to 6-MAM in alkaline medium [17, 18]. No signal is observed at pH 2.0.The variation of peak intensity and peak potential with the pH are presented in Supplementary material, Figure S1.

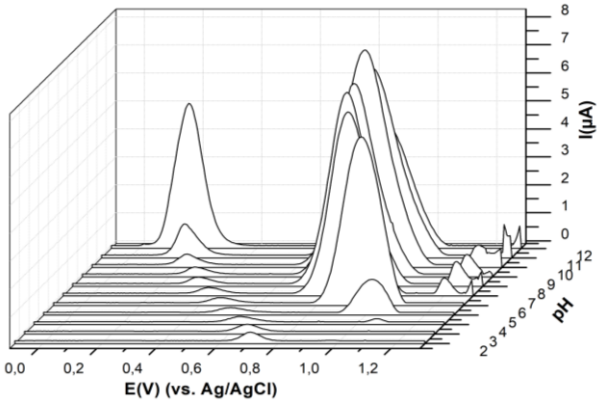


Figure 2. Square wave voltammograms of 500 μM heroin solution in PBS pH 2-12 at GSPE.

Electrochemical screening of heroin and mixing agents at pH 7.0

As observed earlier by our group [5, 6] electrochemical methods are a good screening alternative for adulterated cocaine offering high accuracy of its detection in complex samples. Herein, to improve the accuracy of screening unknown street samples, we extend the electrochemical screening to other illicit drugs i.e. heroin. For this purpose, SWV measurements in PBS buffer pH 7.0 were firstly performed to collect information about the presence of heroin and mixing agents (adulterants, cutting agents and impurities) that were found in heroin samples in the last decades. For this purpose heroin, mixing agents and their 1:1 binary mixtures in PBS pH 7.0 were subjected to SWV on bare GSPE. A list of adulterants and cutting agents commonly added in heroin samples in the last decade was analyzed, including: caffeine, paracetamol, levamisole, quinine, procaine, clenbuterol, maltose, glucose, starch [15, 21, 22, 23]. We also analyzed impurities commonly present in heroin samples from the manufacturing process (e.g. lead, a by-product from lead pots used during manufacturing heroin) and alkaloids which occur naturally in opium (i.e. noscapine, papaverine, scopolamine, codeine). The latter usually occur in traces in heroin samples, however, to prove the concept of electrochemical methods applied for screening of illicit heroin, a generic ratio of 1:1 was also studied in those cases.

Figure 3 shows the square wave voltammograms of 1:1 binary mixtures (100 μM) of heroin and mixing agents. For comparison, the SWV fingerprints of standard solutions of mixing agents are presented in Figure S2, Supplementary material. It can be observed that at pH 7.0 heroin can be detected in mostly all mixtures by its characteristic electrochemical fingerprint, namely the presence of peak 1 (0.81±0.02 V) and peak 2 (0.40±0.02 V), except for the mixture 1:1 with papaverine, in which heroin signal is suppressed at pH 7.0. Paracetamol shows an oxidation peak at 0.42±0.02 V that overlaps heroin peak2, however the heroin detection is still possible by the presence of peak1. As for cocaine, levamisole has a suppression effect on heroin signal. The heroin signal decreases in 1:1 mixtures with levamisole however it is not completely suppressed, as it is in the case of cocaine [21]. Procaine, dextromethorphan, clenbuterol, codeine and scopolamine give rise to oxidation peaks that overlap the peak 1 of heroin. Thus, in their binary mixtures with heroin, the identification of heroin is based solely on the presence of peak 2, related to the oxidation of the 6-MAM present in illicit heroin. Further strategies to enrich the electrochemical fingerprints are thus needed for more accurate detection, in particular for these compounds.

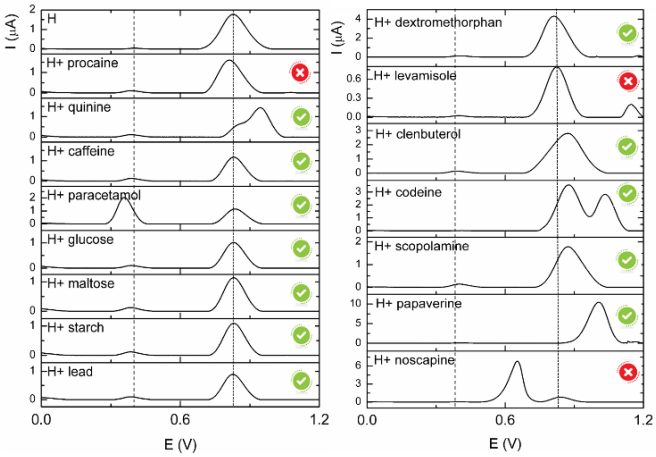


Figure 3. Square wave voltammograms of 100 μM heroin (H) solution and its 1:1 mixtures with mixing agents (100 μM) in PBS pH 7.0 at GSPE. The dotted line represents the oxidation peak 1, while the dash line corresponds to the oxidation peak 2, in illicit heroin containing 6-MAM. Overlapping or suppressed signals Detectable signal for heroin

Electrochemical screening of heroin and mixing agents at pH 12.0

As mentioned in section 1 adjusting the pH to pH 12.0 has an influence on the electrochemical signal of heroin, with a negative potential shift for both peak 1 and peak 2 and an enhanced intensity of peak 2. Considering this, binary mixtures 1:1 of heroin and its mixing agents were analyzed by SWV at pH 12.0 (Figure 4). This strategy allowed for better identification of heroin and its mixing agents, enriching their redox fingerprints. For example, procaine exhibits a shift of its characteristic oxidation peak from 0.79±0.02 V at pH 7.0 to 0.58±0.02 V at pH 12.0. This allows better peak separation from peak 1 of heroin and hence allows their simultaneous detection in a sample. A slight positive shift is observed for heroin in mixture with procaine at pH 12.0. Additionally, the sensitivity to the detection of peak 2 is enhanced, as its intensity greatly increases at pH 12.0, due to fast heroin hydrolysis to 6-MAM. Moreover, peak 2 is revealed at pH 12.0 even in pure heroin (Figure S3, Supplementary Material). Thus, one can affirm that the detection of peak 2 (and its inclusion in the electrochemical fingerprint of heroin) is more reliable at pH 12.0. The better identification reliability of peak 2 at pH 12.0 also comes as a solution in the cases of heroin mixtures with codeine and scopolamine: even though overlaps with peak 1 are not resolved, the identification of heroin in these cases can be accurately based on the presence of peak 2. For clenbuterol, altering the pH to pH 12.0 also gives rise to two anodic waves (although not well resolved), enriching its fingerprint for a more accurate detection in mixture with heroin. Adjusting the pH to pH 12.0 solves the issue of heroin peak suppression in the presence of papaverine, revealing both peak 1 and peak 2 of heroin.

In 1:1 mixture with dextromethorphan heroin peak 1 appears as a shoulder to dextromethorphan peak, in addition to a higher intensity for peak 2, improving the detectability of heroin also in this case. Heroin peak is also revealed as a shoulder in mixtures with noscapine. The SWV scans of mixing agents at pH 12.0 are presented for comparison in Figure S4, Supplementary material.

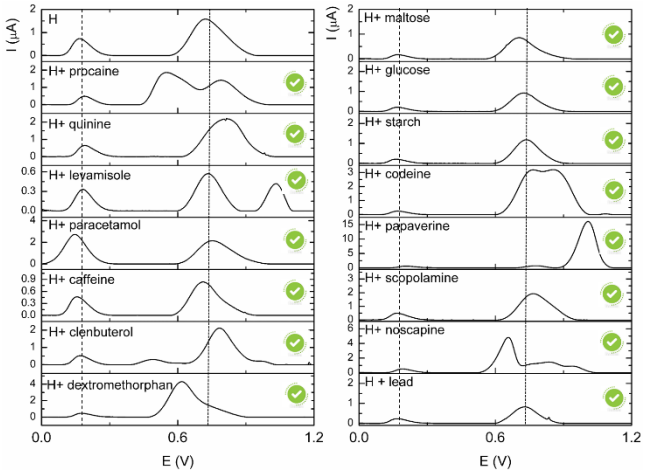


Figure 4. Square wave voltammograms of 100 µM heroin (H) solution and its 1:1 mixtures with mixing agents (100 µM) in PBS pH 12.0 at GSPE. The dotted line represents the oxidation peak 1, while the dash line corresponds to the oxidation peak 2, in illicit heroin containing 6-MAM. Detectable signal for heroin

Electrochemical behavior of heroin and mixing agents with preconditioning at pH 7.0 and pH 12.0

We have demonstrated in our previous work [6] that introducing a preconditioning step can solve issues related to peak suppression/overlap, by electrochemical cleaning of the electrode surface, creating defect sites through the removal of carbon or reducing various functional groups, which seems to be beneficial for the electrochemical response. Zhu et al [24] reported that an electrode pretreatment by applying a negative potential creates alkaline conditions near the electrode surface which may explain the increase and shift in the peak signal upon pretreatment at pH 7.0. To check if the strategy is applicable to heroin samples, SWV with a preconditioning step was performed at pH 7.0 and at pH 12.0. The preconditioning step consisted in applying a fixed potential of -0.8 V for 180s. The preconditioning time was optimized, varying the time from 60s to 180s and 360s for 100 µM heroin solution in PBS pH 7.0. An increase in peak 1 current intensity was observed as the time increased from 60s to 180s. A further increase of the time to 360s did not show a significant increase in the peak intensity, thus 180s was considered optimal (Figure S5, Supplementary).

As seen in Figure 5 introducing a preconditioning step at pH 7.0 and at pH 12.0 proved to be useful for heroin mixtures with quinine and procaine, respectively. A better peak separation was observed for heroin-quinine mixtures with preconditioning at pH 7.0 and a negative shift and a split of procaine peak is observed with preconditioning at pH 12.0, allowing to better identify them by the automatic peak identification. For other mixing agents no added value of introducing a preconditioning step was observed (Figure S6, S7, Supplementary).

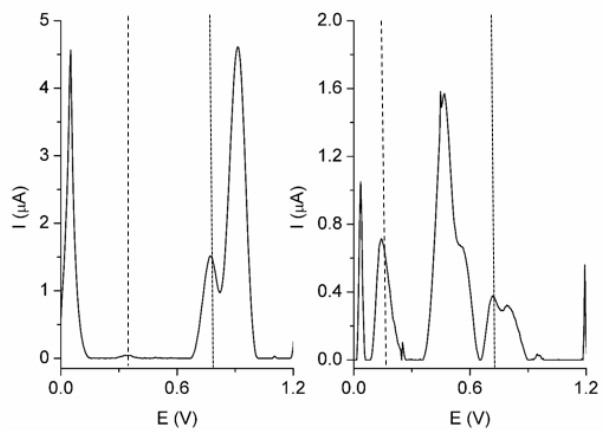


Figure 5. Square wave voltammograms with a preconditioning step of 1:1 heroin mixture with quinine at pH 7.0 (A) and with procaine at pH 12.0 (B) at GSPE. Concentration of heroin, quinine and procaine 100 µM. The dotted line represents the oxidation peak 1, while the dash line corresponds to the oxidation peak 2, in illicit heroin containing 6-MAM.

Electrochemical behavior of heroin and other drugs (cocaine, MDMA, morphine)

To test the capability of electrochemical strategies to (1) discriminate between different types of drugs in order to establish the composition of an unknown seized street sample, and (2) detect drugs simultaneously in drug combinations, binary mixtures of heroin with other drugs were also analyzed by SWV. Cocaine, MDMA and morphine were investigated. Morphine is an opiate drug of abuse that naturally occurs in opium and is the starting compound for heroin synthesis. Therefore, unreacted morphine from the manufacturing process can be also found in illicit heroin samples as impurity. Cocaine can be found in combination with heroin with the street name Belushi, boy-girl, he-she, dynamite, goofball, H&C, primo, snowball, screwball or Murder 1. Heroin combination with MDMA is commonly known as chocolate chip cookie, on the ball or H bomb [23].

A screening of the drugs alone and in binary mixtures was performed by SWV at pH 7.0 and further at pH 12.0, to assess possible fingerprint enrichment by adjusting the pH (Figure 6). For comparison, the electrochemical response of cocaine, MDMA and morphine alone is presented in Figure S8, Supplementary material.

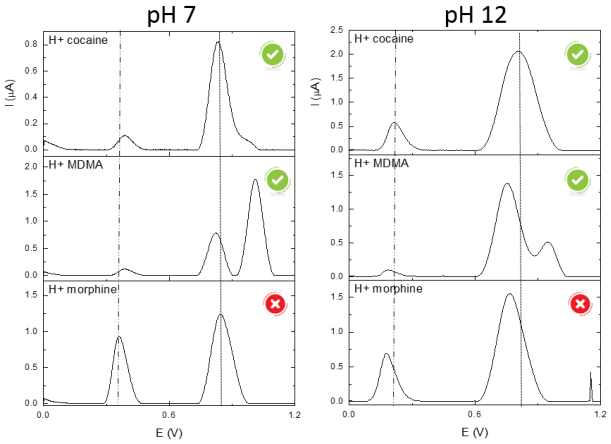


Figure 6. Square wave voltammograms of 1:1 heroin mixture with cocaine, MDMA, morphine at pH 7.0 and at pH 12.0. Concentration of drugs 100 µM. The dotted line represents the oxidation peak 1, while the dash line corresponds to the oxidation peak 2, in illicit heroin containing 6-MAM. Overlapping signals Detectable signal for heroin

In 1:1 heroin-cocaine mixtures at pH 7.0, heroin can be identified by peak 1 (tertiary amine oxidation) and peak 2 (characteristic to 6-MAM), while cocaine oxidation peak appears as a shoulder at around 1.04 V. Thus, it is possible to discriminate heroin from cocaine at pH 7.0 and to detect them simultaneously in a sample by automatic peak identification. Adjusting the pH to 12.0 results in an increase in the current intensity of heroin peak 2, enhancing the accuracy of heroin detection in particular for samples containing pure heroin (6-MAM absent) or low amounts of 6-MAM. Thus, the discrimination between heroin and cocaine is possible also at pH 12.0, by the presence of an additional peak for heroin (peak 2). However at pH 12.0 the cocaine peak overlaps with heroin peak1, making the simultaneous detection of both cocaine and heroin difficult. Thus detection at pH 7.0 is preferred in this case. The differentiation and simultaneous detection of heroin and MDMA in combinations is possible both at pH 7.0 and at pH 12.0. Both the oxidation peaks of heroin (peak 1 and peak 2) and of MDMA (0.94±0.02 V) can be revealed and are better resolved at pH 7.0 compared to pH 12.0. Due to their similar structures simultaneous detection of heroin and morphine cannot be achieved by present electrochemical strategies due to overlapping signals. Morphine also exhibits two oxidation waves at the same potential as heroin. However a discrimination between them is possible at pH 12.0, at which 100 µM morphine solution displays a slightly different feature with a peak split at higher potentials (Figure S8).

Paracetamol is a common adulterant in heroin samples and can be found in adulterated cocaine samples as well. Heroin peak 2, characteristic to 6-MAM oxidation in heroin samples, overlaps the signal of paracetamol both at pH 7.0 and pH 12.0, as shown previously in Figure 3 and 4. Since peak 2 plays an important role in the discrimination and simultaneous detection of heroin and cocaine, it becomes challenging to detect these two drugs in samples adulterated with paracetamol. To offer a solution to this problem and improve the discrimination accuracy between cocaine and heroin the pH of the detection solution was adjusted to pH 5.0 (Figure 7). At pH 5.0 cocaine does not exhibit a signal in the investigated potential window at GSPE, whereas the oxidation signal of heroin, peak1, can be revealed at 1.02±0.02 V in pH 5, making possible their discrimination at pH 5, even in presence of paracetamol (0.50±0.02 V at pH 5). The square wave voltammograms of heroin, cocaine and paracetamol alone at pH 5.0 are presented in Figure S9, Supplementary material.

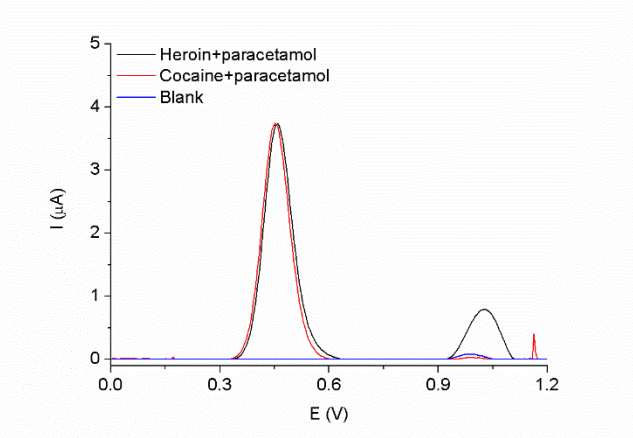
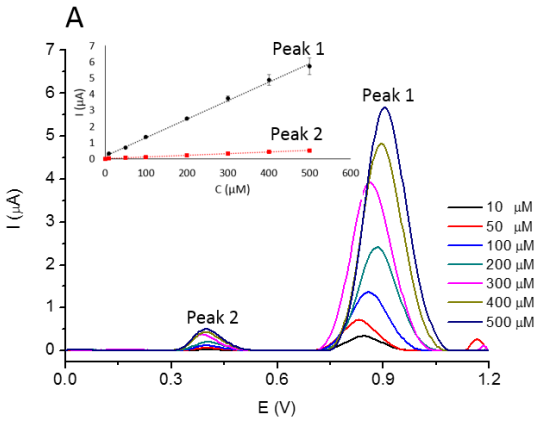


Figure 7. Square wave voltammograms of 1:1 heroin-paracetamol and cocaine-paracetamol mixture at pH 5.0. Concentration of drugs 100 µM. Scan rate 50 mV s^{-1}.

Calibration plot heroin pH 7.0 and pH 12.0

The electrochemical strategies were applied for the determination of heroin at different concentrations. The resulting voltammograms, as well as the dependency of peak current vs heroin concentration are shown in Figure 8. The peak current varies linearly with heroin concentrations up to 500 µM at pH 7.0 and up to 1000 µM at pH 12.0. There is only a relatively small increase in the peak current intensity with the concentration for peak 2, related to the oxidation of the phenol group of 6-MAM at pH 7.0. The regression equation at pH 7.0 was I_p (µA) = 0.012 C (µM) + 0.150 (R^2 = 0.997) for peak1 and I_p (µA) = 0.001 C (µM) + 0.008 (R^2 = 0.995) for peak2. At pH 12.0 the regression equation was I_p (µA) = 0.001 C (µM) + 0.208 (R^2 = 0.998) for peak1 and I_p (µA) = 0.005 C (µM) + 0.082 (R^2 = 0.996) for peak 2. The lowest concentration detected with good reproducibility was 10 µM for both pH 7.0 (RSD 2.3%) and pH 12.0 (RSD 9.5%).



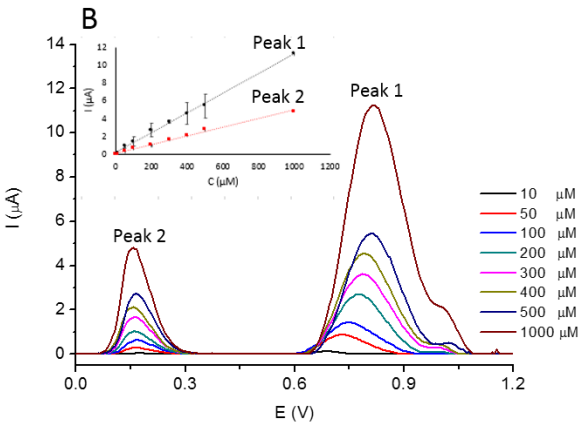


Figure 8. Square wave voltammograms of the determination of different concentrations of heroin at (A) pH 7.0 and at (B) pH 12.0 Inset: respective calibration plot for peak 1 (●) and peak 2 (■)

Application to street sample analysis

The end goal is to quickly detect the presence of heroin in confiscated samples. Heroin samples confiscated by law enforcement authorities were analyzed at NICC, Belgium, using a portable potentiostat connected to a tablet for data output. At least 1 mg of street sample was dissolved in 1 mL PBS buffer pH 7.0 and pH 12.0, respectively and analyzed by SWV. As seen in Table 1 the electrochemical strategies revealed the presence of heroin in all samples both at pH 7.0 and at pH 12.0, except for sample 1 at pH 7.0. Depending on the composition of the sample and the electrochemical behavior of each compound at pH 7.0 and pH 12.0, running a SWV either at pH 7.0 or at pH 12.0 can offer more information on which compounds are present in the sample. For example, in sample 2 and 5 the oxidation signal of papaverine appears at pH 12.0 in addition to the peak of heroin and paracetamol (which are the only peaks revealed at pH 7.0). In these samples papaverine is present in very low amounts, as opposed to 1:1 mixtures studied in section 2, thus no suppression effects were observed at pH 7.0. SWV at pH 12.0 outperforms pH 7.0 also for samples adulterated with dextromethorphan (8, 13, 21, 28, 29) in which the presence of dextromethorphan in the sample can only be revealed at pH 12.0, due to an additional peak appearing at pH 12.0 for dextromethorphan. For sample 3 and 4, the oxidation peak of noscapine is better resolved at pH 7.0 and can be identified by automatic peak recognition, while at pH 12.0 it appears as a shoulder to heroin peak. In samples containing paracetamol the signal of paracetamol is overlapping the signal of 6-MAM. In samples with no paracetamol content the signal of 6-MAM was revealed both at pH 7.0 and at pH 12.0.

Table 1. Electrochemical analysis of heroin street samples at pH 7.0 and pH 12.0.

No	Composition		pH 7.0	pH 12.0
	Compound	**Wt %**		
1	Heroin	12	-	++
	6-MAM	9		
	Caffeine	23		
	Paracetamol	40		
	Noscapine	9		
	Papaverine	<1		
2	Heroin	13	+	++
	6-MAM	5		
	Caffeine	20		
	Paracetamol	37		
	Noscapine	10		
	Papaverine	<1		
3	Heroin	8	++	+
	6-MAM	10		
	Caffeine	9		
	Paracetamol	1		
	Noscapine	4		
4	Heroin	10	++	+
	6-MAM	20		
	Caffeine	14		
	Paracetamol	9		
	Noscapine	5		
	Papaverine	<1		
5	Heroin	19	+	++
	6-MAM	3		
	Caffeine	19		
	Paracetamol	39		
	Noscapine	11		
	Papaverine	<1		
6	Heroin	15	+	+
	6-MAM	4		
	Caffeine	6		
	Paracetamol	70		
7	Heroin	35	+	+
	6-MAM	48		
	Paracetamol	4		
8	Heroin	47	+	++
	6-MAM	5		
	Caffeine	1		
	Paracetamol	17		
	Papaverine	<1		
	Dextrome-thorphan	*		
9	Heroin	8	+	+
	6-MAM	1		
	Noscapine	2		
	Papaverine	<1		
10	Heroin	48	+	+
	6-MAM	13		
	Caffeine	13		
	Paracetamol	13		
	Noscapine	2		
	Papaverine	<1		
	Dextrome-thorphan	*		
11	Heroin	58	+	+/-
	6-MAM	3		
	Caffeine	<1		
	Noscapine	27		
	Papaverine	1		
12	Heroin	49	+	+
	6-MAM	11		
	Caffeine	13		
	Paracetamol	5		
	Noscapine	3		
	Papaverine	<1		
13	Heroin	50	+	++
	6-MAM	6		
	Caffeine	18		
	Dextrome-thorphan	*		
14	Heroin	55	++	+

	6-MAM	8		
	Caffeine	12		
	Noscapine	3		
	Papaverine	<1		
15	Heroin	42	+	+
	6-MAM	16		
	Caffeine	14		
	Noscapine	2		
	Papaverine	<1		
16	Heroin	47	+	++
	6-MAM	7		
	Caffeine	19		
	Papaverine	<1		
17	Heroin	20	+	++
	6-MAM	7		
	Caffeine	17		
	Paracetamol	30		
	Noscapine	13		
	Papaverine	<1		
18	Heroin	47	+	+
	6-MAM	6		
	Caffeine	15		
	Paracetamol	5		
	Noscapine	9		
	Papaverine	<1		
19	Heroin	48	++	+
	6-MAM	13		
	Caffeine	15		
	Noscapine	2		
20	Heroin	58	++	+
	6-MAM	7		
	Caffeine	11		
	Noscapine	6		
	Papaverine	<1		
21	Heroin	43	+	++
	6-MAM	6		
	Caffeine	9		
	Dextrome-thorphan	*		
22	Heroin	24	+	++
	6-MAM	3		
	Caffeine	17		
	Paracetamol	33		
	Noscapine	12		
	Papaverine	<1		
23	Heroin	53	+	+
	6-MAM	2		
	Noscapine	26		
	Papaverine	1		
24	Heroin	17	+	++
	6-MAM	10		
	Caffeine	18		
	Paracetamol	29		
	Noscapine	10		
	Papaverine	<1		
25	Heroin	11	+	++
	6-MAM	6		
	Caffeine	22		
	Paracetamol	43		
	Noscapine	6		
	Papaverine	<1		
26	Heroin	9	+	++
	6-MAM	4		
	Caffeine	9		
	Paracetamol	66		
	Noscapine	5		
	Papaverine	<1		
27	Heroin	40	+	++
	6-MAM	11		
	Caffeine	18		
	Noscapine	11		
	Papaverine	2		
	Lidocaine	*		
28	Heroin	36	+	++
	6-MAM	11		
	Caffeine	19		
	Noscapine	11		
	Papaverine	1		
	Dextrome-thorphan	*		
29	Heroin	39	+	++
	6-MAM	11		
	Caffeine	18		
	Noscapine	11		
	Dextrome-thorphan	*		
	Lidocaine	*		
30	Heroin	36	+	+
	6-MAM	5		
	Caffeine	47		

+ sample positive for heroin
++ improved detectability of compounds present in the sample
* concentration not determined

The exemplary results obtained for the analysis of sample 23 with the portable system is shown in Figure 9. It can be seen that heroin electrochemical fingerprint (peak 1 and peak 2) is revealed both at pH 7.0 and at pH 12.0. Scanning at pH 7.0 allows to reveal the oxidation peak of noscapine (around 0.62 ± 0.02 V) and the peak of papaverine (around 1.00 ± 0.02 V) with the given experimental setup, the latter appearing as a shoulder-peak at pH 7.0. Papaverine peak is better resolved at pH 12.0, however due to negative shifts of peaks, noscapine cannot be detected in this case, as its signal is overlapped by heroin. This shows that SWV screening using the dual pH strategy, pH 7.0 and pH 12.0, improves detectability of compounds present in a sample, offering more information on the composition of a sample.

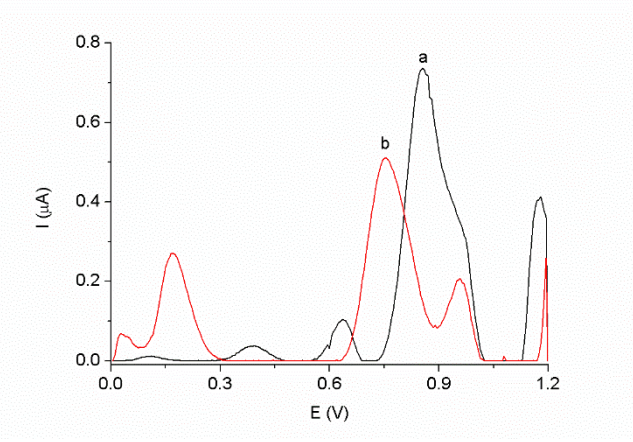


Figure 9. Square wave voltammograms of the analysis of sample 23 (Table 1) at (a) pH 7 and (b) pH 12. Scan rate 50 mV s^{-1}.

Conclusion

In this work, we have demonstrated for the first time that a dual pH electrochemical strategy, consisting of SWV screening of illicit heroin samples at pH 7.0 and at pH 12.0, allows to quickly detect heroin and common mixing agents in street samples. We elucidated the unique electrochemical fingerprint of heroin at pH 7.0 and pH 12.0 on bare graphite screen-printed electrodes. A detection limit of 10 µM was obtained for heroin in a linear range up to 500 µM at pH 7.0 and up to 1000 µM at pH 12.0. We showed that adjusting the pH from 7.0 to 12.0 lead to a better accuracy of the detection of heroin in mixtures with procaine, clenbuterol, scopolamine, codeine and papaverine. In addition, introducing a preconditioning step by applying a fixed negative potential at pH 7.0 and pH 12.0 further improves the accuracy for the detection of heroin-procaine and heroin-quinine mixtures, respectively. We demonstrated that simultaneous detection and discrimination between heroin and other drugs (cocaine, MDMA) is also possible by SWV at pH 7.0 and pH 12.0. However due to the similarity in the chemical structure the discrimination between heroin and morphine was not possible. Using a buffer of pH 5.0 was proved to be useful to differentiate between heroin and cocaine in samples containing paracetamol. The dual pH strategy was successfully applied to detect heroin in street samples seized in Belgium. Together with the dual pH strategy applied for cocaine samples analysis in our previous work, these findings set the foundation of developing a generic strategy for multi-detection of illicit drugs. To achieve this final goal further studies are needed to elucidate the electrochemical fingerprint of several other illicit drugs and their common adulterants and to better discriminate between drugs with similar chemical structures.

ASSOCIATED CONTENT

Supporting Information

Variation of peak potential with the pH; Square wave voltammograms of mixing agents solution in PBS pH 7.0; Square wave voltammograms of pure heroin at pH 12.0 and pH 7.0 onto GSPE; Square wave voltammograms of mixing agents solution in PBS pH 12.0; Optimization of preconditioning time at -0.8 V for 100 µM heroin solution in PBS pH 7.0; Square wave voltammograms of 100 µM heroin, mixing agents and their 1:1 mixtures in PBS pH 7.0 and pH 12.0 at GSPE with a preconditioning step; Square wave voltammograms of 100 µM cocaine , MDMA and morphine solutions in PBS pH 7.0 and 12.0 at GSPE; Square wave voltammograms of 100 µM cocaine, heroin and paracetamol solutions in PBS pH 5.0 at GSPE. This material is available free of charge via the Internet at http://pubs.acs.org.

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