Article

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Fluorescently labeled cyclodextrin derivatives as exogenous markers for real-time transcutaneous measurement of renal function

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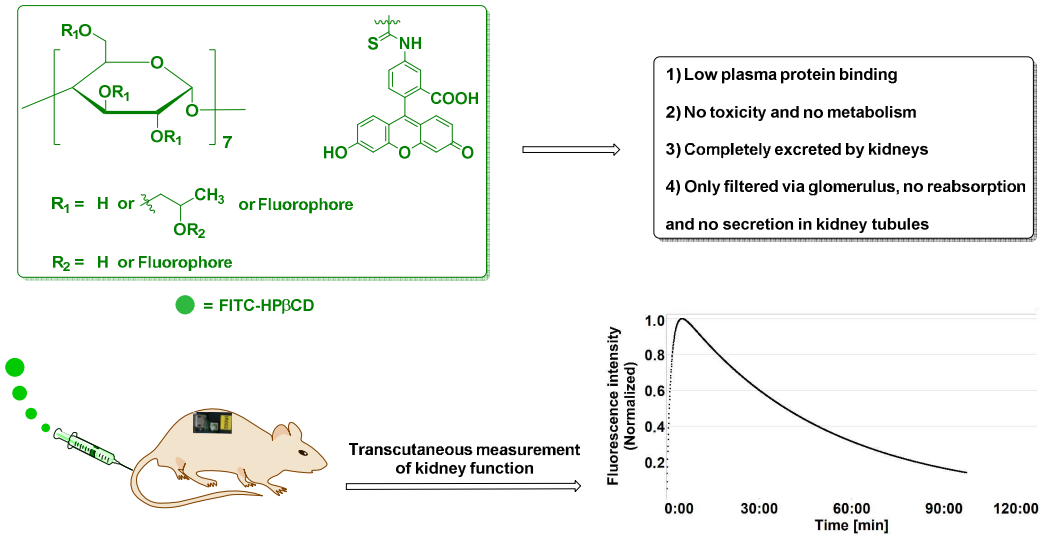
Abstract Graphic



Abstract

Evaluation of renal function is crucial for a number of clinical situations. Here, we reported a novel exogenous fluorescent marker (FITC-HPβCD) to real-time assess renal function by using a transcutaneous fluorescent detection technique. FITC-HPβCD was designed based on the principle of renal clearance of designed drugs. It displays favorable fluorescent properties, high hydrophilicity, low plasma protein binding, high stability in porcine liver esterase as well as in plasma and non-toxicity. More importantly, FITC-HPβCD can be efficiently and rapidly filtered by glomerulus and completely excreted into urine without proximal tubular reabsorption or secretion in rat models. Additionally, the marker was well tolerated and near 100% urinary recovery of the given doses and no metabolism were found. Relying on this novel kidney function marker and transcutaneous devices, we demonstrate a rapid, robust and convenient approach for real-time assessing renal function without the need of time-consuming blood/urine sample preparation. Our work provides a promising tool for noninvasive real-time monitoring of renal function in vivo.

Keywords: Renal function, Fluorescent markers, Glomerular filtration rate, Transcutaneous measurement, Cyclodextrin

Introduction

Renal damage affects the ability of the kidney to remove xenobiotics and metabolic products from blood.[1, 2] Accurate measurement of renal function is crucial for detection and treatment of kidney failure.[3] Especially in the case of impaired kidney function, accurate assessment of renal function is essential for detecting renal failure in early stage of the disease, evaluating interventions and monitoring changes of function over time.[3, 4] Glomerular filtration rate (GFR) is considered as the best indicator for overall renal function.[5, 6] GFR cannot be measured directly, the most common method of measuring GFR is based on the concept of clearance, the renal clearance of a substance can be defined as the volume of plasma from which that substance is completely cleared per unit time.[7, 8]

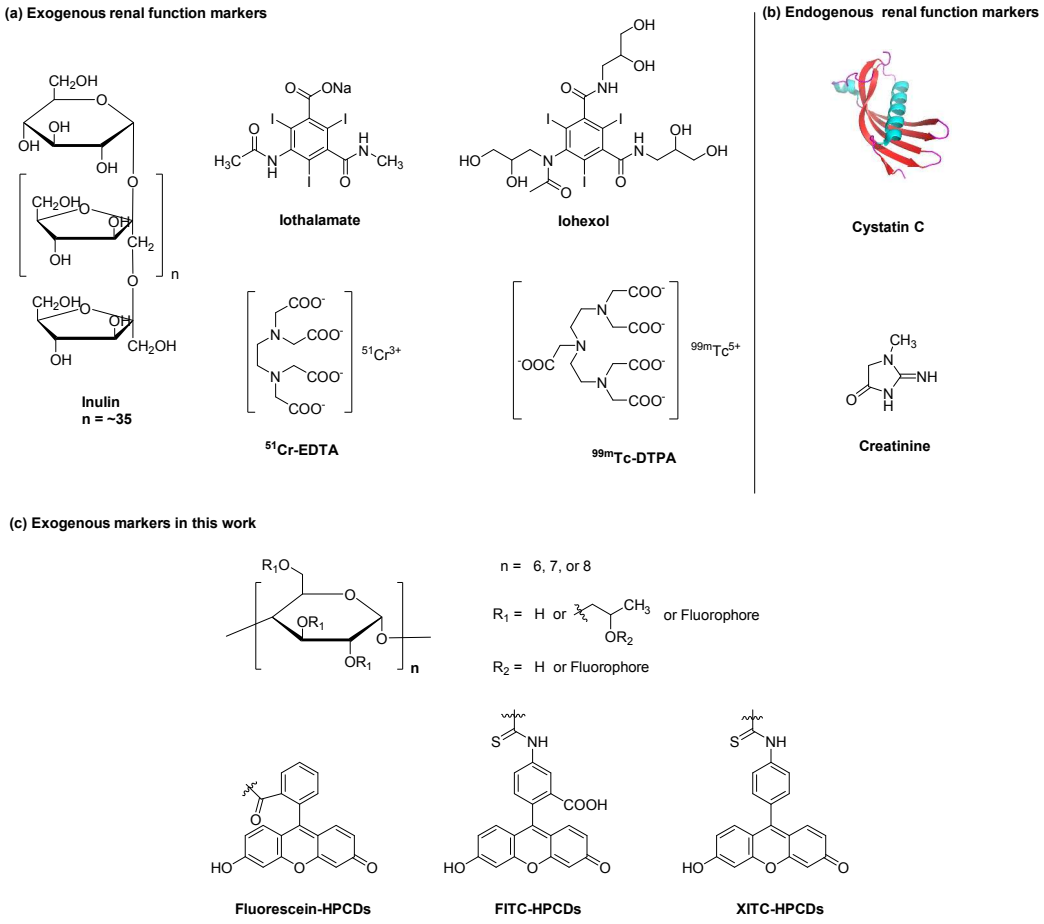
Endogenous markers, such as creatinine and cystatin C, as well as several exogenous agents including inulin, ^{99m}Tc-DTPA and iothalamate (Scheme 1 and Table S2) have been developed to determine GFR in the past several decades. Plasma creatinine concentration is commonly used to estimate GFR, however, creatinine is a product of the metabolism of creatine in muscles, therefore this parameter may be misleading as it is affected by age, gender, muscle mass, diet and many other anthropometric variables.[9] Moreover, many studies revealed that creatinine is not only filtered by the glomerulus, but also secreted by proximal tubule cells, leading to creatinine clearance exceeds GFR.[1, 9, 10] Furthermore, plasma clearance of exogenous agents including iothalamate and

^{99m}Tc-DTPA, have been used to measure GFR. Those methods suffer from complexity of *ex-vivo* handling of blood/urine samples or disposal of radioactivity.[1] GFR can be determined by injecting inulin, since inulin is neither reabsorbed nor being secreted by the proximal tubule after glomerular filtration, so its rate of excretion is directly proportional to the rate of filtration of water and solutes across the glomerular filter. Therefore, inulin is considered as the 'gold standard' agent.[11] Nevertheless, it is difficult to handle due to poor water solubility and limited availability.[11] Also, determinations of the plasma/urinary clearance of exogenous renal markers are cumbersome, invasive and very time-consuming, due to the requirement of multiple blood/urine sampling and tedious samples analysis by HPLC.[1, 12]

Many attempts had been made to overcome those limitations. Recently, fluorescent GFR markers have gained much attention. However, very few fluorescent compounds have been reported as true GFR markers so far. Only two kinds of fluorescent GFR markers have been reported from animal experiments. First, Dorshow *et al.* made great efforts by focusing on the development of fluorescent GFR markers based on two general approaches, one of the approaches involved enhancing the fluorescence of known or existing renal agents, which are intrinsically poor emitters, such as lanthanide metal complexes. However, the results suggested that these complexes are excreted not only *via* glomerular filtration, but also through tubular secretion, leading to a bias in GFR measurement,[13] the other approach was based on transforming highly fluorescent dyes into hydrophilic and anionic substances to force them to be excreted

by kidneys. Although hydrophilic pyrazine-dicaboxylic acid derivatives were developed, the sophisticated synthesis routes made them difficult to produce and expensive.[14-16] Secondly, earlier, inulin has been engineered in its fluorescein isothiocyanate conjugated variant for a single-bolus injection method in conscious animals,[17, 18] its elimination kinetics is typically obtained by measuring the fluorescent values in plasma over a specific period time after the bolus injection. Despite the highly reproducible results provided that no longer required urine sampling, the repeated blood sampling makes the method be stressful and still in an invasive manner, moreover, the necessity to heat and dialyze the FITC-inulin solution for removing residual unbound FITC makes the procedure be cumbersome.[17, 18] In keeping with these observations, it is urgent to overcome the poor solubility of FITC-inulin, as well as plasma sample collection and analysis. In our previous studies, we, on one hand, successfully developed FITC-sinistrin instead of FITC-inulin,[19-21] due to its better water solubility and no need to dialyze before injection; On the other hand, we developed a noninvasive transcutaneous measurement for the elimination kinetics of fluorescent FITC-sinistrin marker based on a miniaturized electronic device attached to the skin.[22-28] The major advantage of this approach is their independence from blood/urine sampling and laboratory assays. Therefore, allowing renal function assessment in real-time and making the evaluation of rapid changes in renal function possible, for example, in acute renal failure. Importantly, more precise results of the plasma clearance can be obtained *via* transcutaneous real-time measurement, which relies on a high number of data-points rather than a limited number of data-points

from blood/urine sampling. Nevertheless, both inulin and sinistrin suffered from their inherent limitations such as high cost, limited availability, sophisticated extraction and purification from plants roots. Therefore, there is an unmet challenge to develop novel fluorescent GFR markers for noninvasive real-time assessing renal function.



Scheme 1. Structures of (**a**) exogenous, (**b**) endogenous [29] renal function markers and (**c**) novel exogenous markers Fluorescein-HPCDs, FITC-HPCDs and XITC-HPCDs.

Here, we report 2-hydroxylpropyl-cyclodextrins (HPCDs) based fluorescent markers (Scheme 1c) for transcutaneous assessment of kidney function. FITC-HPCDs markers are judiciously designed by combining the basic principle of renally cleared drugs and

the knowledge of a cyclodextrin-based drug delivery system. These markers can be easily synthesized, have favorable fluorescent properties, high hydrophilicity, low plasma protein binding (PPB), high stability in porcine liver esterase as well as in plasma and non-toxicity. More significantly, FITC-HPβCD can be excreted efficiently and rapidly through kidneys into urine without reabsorption and secretion in kidney tubule. This is in agreement with a previous study that 99% administered cyclodextrin can be excreted to urine within 12 h.[30] High urinary recovery further demonstrates that it is completely renally cleared without metabolism *in vivo*. Due to these favorable properties, FITC-HPβCD has a high potential to be an exogenous marker for noninvasive real-time transcutaneous assessment of renal function.

Results and discussion

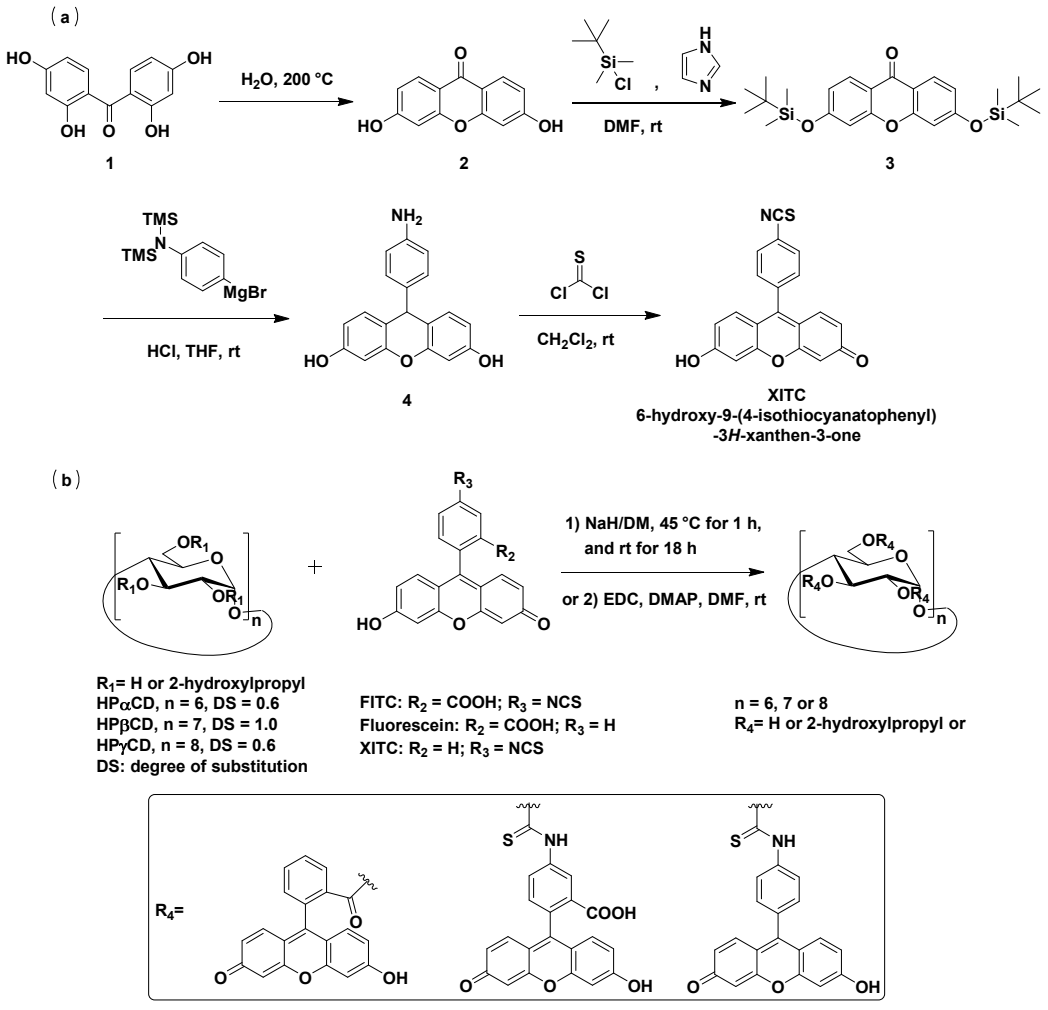
Design and synthesis

An ideal exogenous fluorescent marker for transcutaneous assessment of GFR should meet certain requirements[14] such as 1) the excitation and emission wavelength in the visible region or near infrared range; 2) highly hydrophilicity and neutral or anionic charge; 3) very low or no PPB; 4) non-toxicity and no metabolism *in vivo*; 5) no reabsorption and no secretion in kidney tubules, filtrated only by the glomerulus; and 6) easily to produce with low costs. It is necessary to take all of these characteristics into account for a rational GFR marker design. To meet these criteria, a series of fluorescent markers were designed comprising the two key functional components: 2-hydroxylpropyl-CDs (HPCDs) and fluorophores. Firstly, introducing HPCDs is attempted to increase water solubility, decrease PPB and accelerate excretion for

fluorescent markers. Among various native cyclodextrins (CDs) and CDs derivatives, 2-hydroxylpropyl-αCD, -βCD and -γCD (abbreviated as HPαCD, HPβCD and HPγCD in below) not only have better water solubility than their native CDs (Table S3), but are also more stable to resist the hydrolysis by α-amylases of either porcine or human origin.[31] γCD can be hydrolyzed relatively fast and extensively (80% in 24 h) by α-amylases.[31] However, the degradation rates of αCD, βCD, HPαCD, HPβCD are limited and slow (only 2% in 24 h) by porcine pancreatic α-amylases.[31] The merits of no toxicity resulted in a FDA approval ten years ago.[32-34] Additionally, their narrow molecular weight distribution, low costs, sufficient availability[32-35] make them be an ideal backbone of GFR agents. Secondly, fluorescent dyes belonging to the xanthene family with appealing properties such as physiological stability and safety profile, were employed for labeling HPCDs. Furthermore, we expanded our panel of xanthene fluorophores based on decarboxylated FITC, referred as XITC (Scheme 2a), to study the different conjugation bonds and sites between fluorophore and HPCDs systematically. It is noticeable that anionic and neutral substances are preferentially cleared through the renal system,[14] therefore, rhodamine based dyes were not chosen as fluorophores for labeling due to the positive charge of the aniline nitrogens or diethylaniline group. The three resulting markers possess different covalent conjugation bonds and net molecular charge, which are likely to show different pharmacokinetics and pharmacodynamics.

The general synthetic routes of FITC-HPCDs, Fluorescein-HPCDs and XITC-HPCDs are illustrated in Scheme 2. The synthesis of compound XITC was carried out

following an efficient synthetic procedure[36-38]depicted in Scheme 2a. Bisphenolic precursor 2 can be easily accomplished under high temperature in special pressurized flasks. Based on a nucleophilic addition of Grignard derivative to a TBDMS-protected 3, 6-dihydroxy-xanthenone and a subsequent dehydration with aqueous hydrochloric acid,[36, 39] the corresponding amine product 4 was obtained. Treatment of this compound with an excess of thiophosgene under basic conditions yielded the isothiocyanate product XITC. The synthesis of three different markers is easily done in a one-step reaction (Scheme 2b).[40-42] All intermediates and markers were characterized by ^{1}H-NMR, ^{13}C-NMR and LR-MS.



Scheme 2. (**a**) Synthesis of decarboxylated FITC, XITC. (**b**) Synthesis of Fluorescein-HPCDs, FITC-HPCDs and XITC-HPCDs.

Physicochemical characteristics and optical properties

The spectroscopic and physicochemical properties are summarized in Table 1. All conjugated compounds showed absorption peaks in the wavelength range between 490 nm to 500 nm either in PBS or Sprague Dawley (SD) rat plasma (Table 1, Figure 1a and S2), by irradiation at 480 nm, all the markers displayed emission peaks around 520 to 530 nm, which is consistent with the spectra of their free dye. Therefore, the introduction of HPCDs on the fluorophore moiety did not cause shift on the spectra. Notably, their spectrum is effectively matching with the configuration of the transcutaneous device, which is composed of two light-emitting diodes with excitation wavelength at 480 nm and a photodiode for emission wavelength detection at 520 nm. Despite XITC is having a simple structure, it is a novel compound in the xanthene family. Compared to FITC, the removal of carboxylic acid group on the *meso* aryl ring for eliminating the negative charge did not result in change in absorbance and emission spectra. However, the extinction coefficient of XITC is clearly lower than that of FITC[43] and fluorescein[44] (Table 1). This result is consistent with previous studies showing, that the removal of a carboxylic acid group on the *meso* aryl ring allows the benzene moiety a free rotation, leading to a reduction of the extinction coefficient as well as a fluorescent quantum yield.[39]

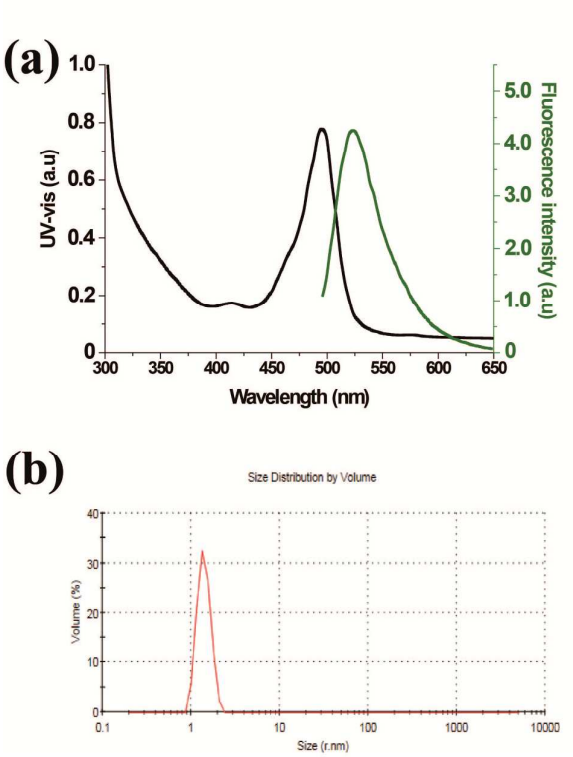


Figure 1. (**a**) Absorption and emission spectra of FITC-HPβCD in rat plasma. (**b**) The size of FITC-HPβCD was analyzed by DLS.

Investigations of matrix-assisted laser desorption/ionization (MALDI) mass spectrometry provided further evidence for fluorophore functionalized HPCDs. In Figure 5b the mass of FITC-HPβCD features five peaks on the right part of the spectrum at m/z = 1720.235, 1778.272, 1836.320, 1894.366 and 1952.403 Da, corresponding to the calculated mass of native HPβCD plus FITC, respectively. A distribution corresponding to the mass of unmodified native HPβCD is also observed at m/z = 1331.368, 1389.395, 1447.423, 1505.459, 1563.495 Da on the left part of the spectrum. 2D (^{1}H-^{1}H NOESY) spectra of FITC-HPβCD and Fluorescein-HPβCD were investigated as shown in Figure S23 and S24, the cross-peak in the NOESY spectrum of both FITC-HPβCD and Fluorescein-HPβCD clearly demonstrates that the

HPCD's interior protons gave the NOE correlations with the aromatic protons of xanthene moiety in either FITC or Fluorescein. The protons of δ 6.7-7.1 ppm were assigned to the xanthene protons and exhibit cross peaks with the HPCD protons (δ 3-4 ppm), suggesting a part fluorophore moiety is encapsulated into the cavity of HPβCD. Distribution coefficient calculations using the JChem plugin of ChemAxon indicated that all the markers had excellent hydrophilicity with the Log D value at pH 7.4 below -5 and varied with different dyes conjugation and HPCDs (Table 1). The net charge of the compounds spans a range from 0 to -1, depending on the absence or functionalization of carboxylic acids. The degree of labeling (DOL)[45] is defined as the average number of dye molecules coupled to HPβCD, the DOL of all the markers were determined as shown in Table 1 and the low DOL (< 0.13) is aim to preserve the properties of HPCDs. Although the DOL of XITC-HPCDs is higher than that of FITC-HPCDs and Fluorescein-HPCDs, their absorbance and emission intensity is lower than FITC-HPCDs and Fluorescein-HPCDs in the same concentration. This is ascribed to the low extinction coefficient and fluorescent quantum yield of XITC, suggesting a higher dose of XITC-HPCDs might be needed in animal experiments.

Aggregation analysis

It has been postulated that macromolecules over 70 kDa or big nanoparticles cannot pass through the glomerular filter into urine under normal conditions.[46] In addition, the possible presence of βCD aggregates in a critical aggregation concentration 3 mM βCD was determined by Dynamic light scattering (DLS) in previous studies.[47-50] Therefore, DLS measurements of FITC-sinistrin, FITC-HPCDs and

Fluorescein-HPCDs at 3 mM concentrations in aqueous solutions were performed to further investigate their aggregation phenomenon (Figure 1b, S5 and Table S8). The hydrodynamic diameter of FITC-sinistrin is roughly 21.9 nm, which is likely due to a molecular weight range of 2000 Da to 6000 Da. Mean diameters in size distribution by volume ranging from 0.6 nm to 3 nm for FITC-HPCDs and Fluorescein-HPCDs were observed. Based on these results and the actual value of the outer diameter (1.46 nm, 1.54 nm and 1.75 nm) and the height (0.79 nm) of αCD, βCD and γCD, respectively (Table S3), we conclude that each of the markers is in its monomeric unit or containing 2 or 3 units at most.

Table 1 Photophysical properties of free dyes and their HPCD based markers.

Entry	λabs (nm) PBS/Plasma	λem (nm) PBS/Plasma	Stokes shift (nm)	ε ($M^{-1}cm^{-1}$)	Net charge (pH = 7.0)	MW [Da]	Log D (pH=7.4)	[a]DOL
FITC	494/496	520/523	26	70000	-1	389.38	-0.70	NA[c]
FITC- HPαCD	490/494	522/525	32	ND[b]	-1	1400 - 1800	-9.30	0.081
FITC- HPβCD	490/494	522/525	32	ND	-1	1700 - 2100	-10.70	0.080
FITC- HPγCD	490/494	522/525	32	ND	-1	2000 - 2400	-10.95	0.082
Fluorescein	494/498	520/525	26	68000	-1	332.31	-1.30	NA
Fluorescein - HPαCD	498/500	534/537	36	ND	0	1400 - 1750	-5.53	0.055
Fluorescein - HPβCD	498/500	534/537	36	ND	0	1700 - 2050	-6.93	0.043
Fluorescein - HPγCD	498/500	534/537	36	ND	0	2000 - 2350	-8.33	0.049
XITC	494/500	530/531	36	16800	0	345.04	3.06	NA
XITC- HPαCD	498/500	530/531	32	ND	0	1400 - 1760	-5.55	0.101
XITC- HPβCD	498/500	530/531	32	ND	0	1700 - 2060	-6.95	0.123
XITC- HPγCD	500/500	530/531	30	ND	0	2000 - 2360	-7.20	0.114

[a]DOL: degree of labeling. [b]ND: not determined. [c]NA: not applicable.

Plasma protein binding

Of particular significance for the suitability of fluorescent markers as GRF markers is the knowledge of their interaction with plasma proteins, because binding to proteins

influences the resulting pharmacokinetics, including bio-distribution and excretion.[51] PPB studies were carried out for all of the markers using the assay described before.[52-54] Each of the markers was incubated with rat plasma at 37 °C for 1 h. The incubated markers were separated from nonabsorbed protein by equilibrium dialysis of PBS against dye-protein stock solution using a two-chamber dialysis set-up. After 24 h the concentrations of markers in both PBS and plasma were determined. As shown in Table 2 and Table S9-S17, all the markers exhibited very low PPB (< 10%), comparable to or even lower (i.e., better) than some of the 'gold standard' renal markers such as iothalamate, ^{51}Cr-EDTA and ^{99m}Tc-DTPA (Table S2). Furthermore, the free fluorophores adsorb to a larger amount of protein than HPCDs based markers, for example, fluorescein exhibits 93.1% PPB,[55] thereby reflecting a greater tendency for proteins to bind to hydrophobic compound. In fact, most oral drugs have a lipophilic physicochemical property, which is associated with higher PPB and hepatic clearance; on the contrary, renally cleared drugs are hydrophilic and usually have a low PPB.[56] In this study, the extremely low PPB of HPCD based markers was attributed to the introduction of hydrophilic HPCDs on those hydrophobic fluorophores structures, which increases their hydrophilicity and minimizes non-specific interactions with serum proteins.

Stability studies in porcine liver esterase and plasma

To determine the stability of conjugation bonds between HPCDs and fluorophore, we co-incubated HPβCD based markers with porcine liver esterase (PLE) for 24 h, and then analyzed their stability with HPLC. No degradation was observed for all of

HPβCD based markers (Figure S6), as indicated by no appearance of free fluorophore peak in HPLC chromatographs when compared to three control measurements, including PLE, free fluorophore and the corresponding marker, respectively. The ester bond of Fluorescein-HPβCD in PLE is stable, which may be attributed to the effect of steric hindrance.[57] To gain further insight into the stability of these markers in plasma, we co-incubated all the HPβCD based markers with plasma. Similarly, no degradation was found after 24 h of incubation with rat plasma (Figure S7). The results revealed that HPβCD based markers are stable in both PLE condition and plasma *in vitro*.

Cell viability evaluated by MTT assay

The cytotoxicity of FITC-HPβCD and Fluorescein-HPCDs was evaluated by using 3-(4, 5-dimethyl-2-thiazoly)-2, 5-diphenyltetrazolium bromide (MTT) assay, in conditionally immortalized human renal proximal tubule cell line (ciPTEC).[58] The results (Figure 2 and S8) show that FITC-HPβCD and Fluorescein-HPCDs did not affect the viability of both of the two cell types tested (organic anion transporters 1 or 3 (OAT1 or OAT3) transfected), as compared to the control group with untreated cells, suggesting these markers have no significant cytotoxic effect in representative human renal cell lines. These non-toxicity results are also in agreement with previous reports using βCD derivatives on other cell lines.[59]

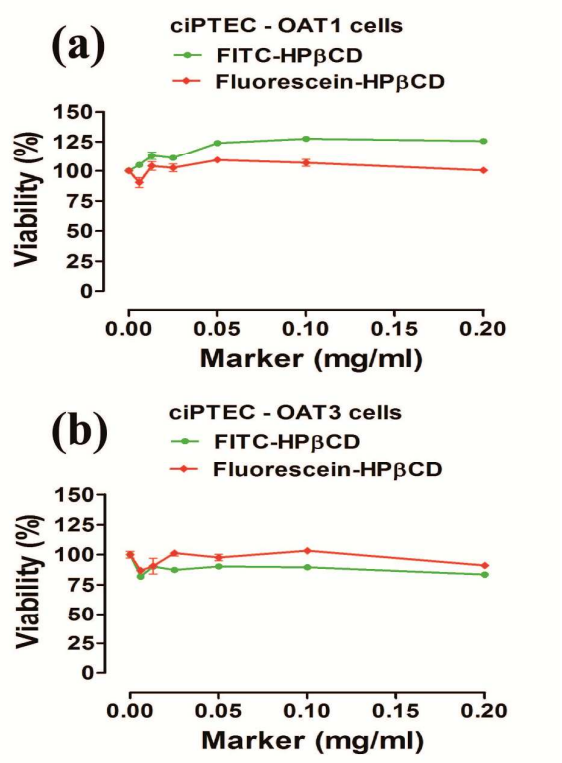


Figure 2. (**a**) Cell viability of ciPTEC-OAT1 and (**b**) ciPTEC-OAT3 cells incubated with FITC-HPβCD and Fluorescein-HPβCD in MTT assays.

Table 2 PPB, urinary recovery and half-life with or without probenecid-treatment

Substance	PPB [%]	Urinary Recovery [%]	$T_{1/2}$ without Probenecid [min]	[b] $T_{1/2}$ with Probenecid [min]	[c] Changes in half-life [%]
FITC- HPαCD	7.1	99.1 ± 2.6 (3)	38.0 ± 4.7 (6)[d]	32.2 ± 5.8 (6)	-15.3
FITC- HPβCD	2.3	103.4± 4.1 (3)	24.1 ± 3.2 (6)	23.6 ± 6.6 (6)	-2.1
FITC- HPγCD	2.8	100 ± 6.7 (3)	20.2 ± 3.2 (6)	18.1 ± 2.7 (9)	-10.9
Fluorescein - HPαCD	0	57.7 ± 2.1 (3)	7.8 ± 4.3 (6)	13.3 ± 6.6 (6)	+70.5
Fluorescein - HPβCD	0	52.2 ± 8.5 (3)	7.3 ± 2.8 (7)	9.6 ± 3.7 (7)	+31.5
Fluorescein - HPγCD	2.4	44.3 ± 3.1 (3)	6.3 ± 1.3 (7)	9.4 ± 2.5 (7)	+49.2
XITC- HPαCD	9.5	ND[a]	ND	ND	ND
XITC- HPβCD	7.7	103.2 ± 5.4 (3)	31.3 ± 7.0 (3)	32.2 ± 4.8 (3)	+2.9
XITC- HPγCD	9.6	ND	ND	ND	ND

[a]ND: not determined. [b]$T_{1/2}$: clearance half-life. [c]Changes in half-life: $[T_{1/2\ Probenecid} - T_{1/2\ without\ Probenecid}]/[T_{1/2\ Probenecid}]$. [d](n): number of rats.

Transcutaneous measurement of renal function in rat models

Encouraged by those excellent properties *in vitro*, we proceeded to investigate

whether these HPCDs based markers can be excreted by kidneys in rats by using noninvasive transcutaneous measurements. The principles and methods of the transcutaneous technique are described in experimental section and shown in Figure 3a-c. Fluorescence elimination curves and kinetic parameters of all the markers can be found in Figure 3, Figure S9 and Table 2. Taken FITC-HPβCD as an example (Figure 3d), the clearance curves of FITC-HPβCD returned to background within 2 h after intravenous injection, suggesting it was excreted completely in this period and has a clearance half-life of 24.1 ± 3.2 min (Table 2). Furthermore, to determine whether FITC-HPβCD can be reabsorbed or secreted in addition to glomerular filtration in kidneys, probenecid, an inhibitor of organic anion transporter (OAT) proteins in kidney tubules,[60, 61] was administered to block a tubular reabsorption and secretion pathway, then fluorescence elimination curves were also measured transcutaneously for the same rats. The fluorescent signals descended to baseline and it has a similar clearance half-life (23.6 ± 6.6 min) when compared to without probenecid treatment (Figure 3e and Table 2). The clearance half-life of FITC-HPCDs either in the absence or presence of probeneicd follow the order FITC-HPαCD > FITC-HPβCD > FITC-HPγCD, supporting that the elimination goes faster with increased size of HPCDs. Similar phenomena were observed for Fluorescein-HPCDs (Fluorescein-HPαCD > Fluorescein-HPβCD > Fluorescein-HPγCD). The clearance half-life of the tested markers also varied with the fluorophore scaffold used, for example, XITC-HPβCD > FITC-HPβCD > Fluorescein-HPβCD. Either with or without probenecid treatment, Fluorescein-HPCDs were excreted extremely fast

(Figure 3f and 3g) and have a shorter clearance half-life than FITC-HPCDs or XITC-HPβCD. In FITC-HPCDs, FITC-HPαCD and FITC-HPγCD have a slight tubular reabsorption, because shorter clearance half-lifes were observed in the presence of probenecid (Figure 4a). In contrast, Fluorescein-HPCDs showed a significant higher half-life with probenecid treatment, which indicates tubular secretion in kidneys. Surprisingly, a negligible difference in half-life between the absence and presence of probenecid treatment for FITC-HPβCD and XITC-HPβCD was observed (Figure 4a), suggesting that FITC-HPβCD and XITC-HPβCD exhibit no tubular reabsorption or secretion, and are cleared by glomerular filtration solely. Bland-Altman plots for transcutaneous measurement in the presence and absence probenecid treatment are depicted in Figure S10.

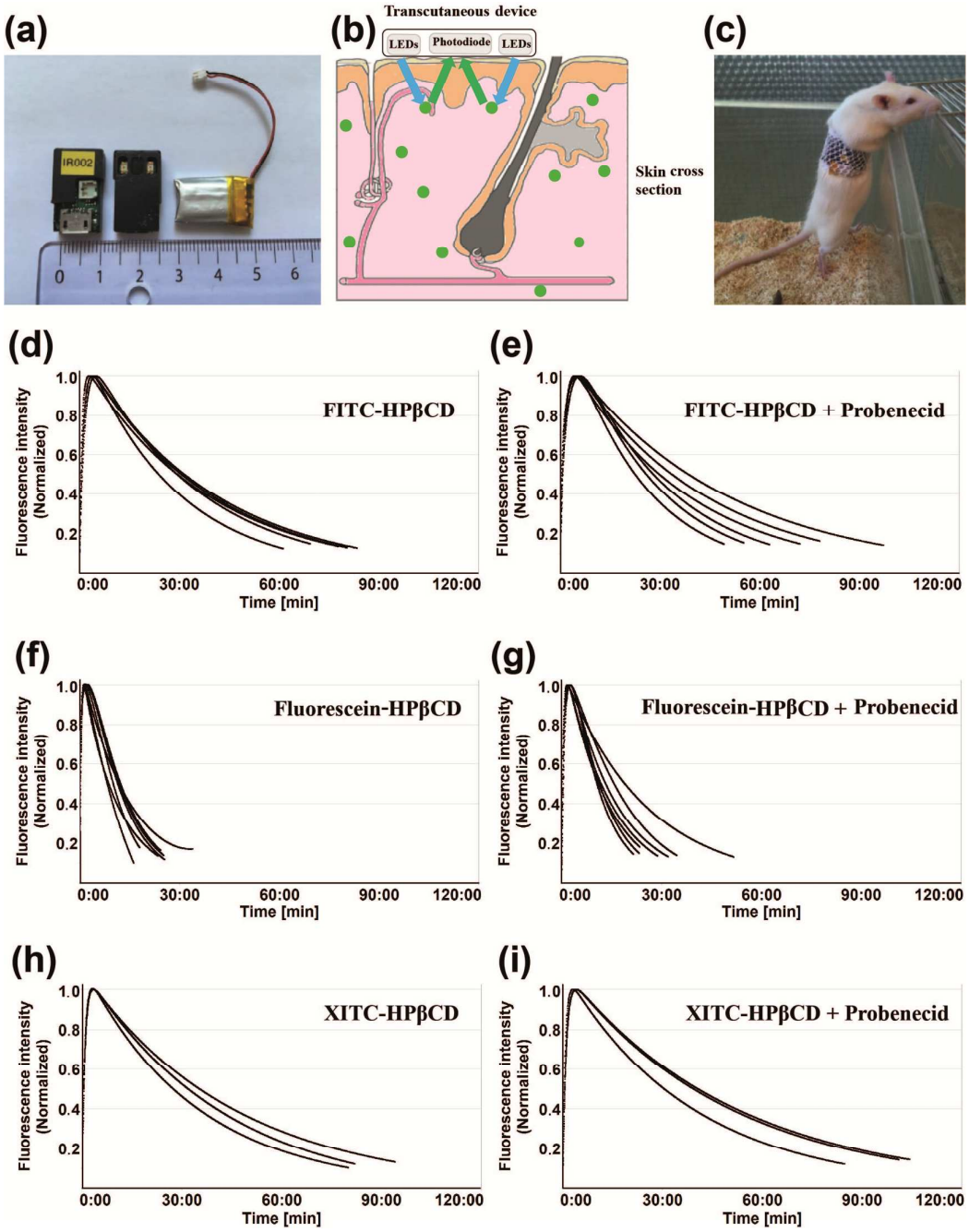


Figure 3. (**a**) Miniaturized transcutaneous devices and a battery used for the transcutaneous measurement of kidney function. (**b**) Fluorescent markers diffused from the vascular space to the interstitium after intravenously administration and its excretion was determined using a miniaturized electronic transcutaneous device. (**c**) A conscious SD rat is under transcutaneous measurement with an attached device.

Elimination curves of FITC-HPβCD (**d** and **e**, n=6), Fluorescein-HPβCD (**f** and **g**, n=7) and XITC-HPβCD (**h** and **i**, n=3) by transcutaneous measurements in SD rats models in the absence and presence of probenecid treatment.

Urinary recovery and metabolism studies

A mandatory prerequisite for an ideal renal function marker is to recover completely in urine and have no metabolism *in vivo*, therefore we conducted recoveries of the injected doses using *in vivo* experiments with metabolic cages. Each marker was injected intravenously into rats. As shown in Figure 4, Figure S11 and Table S18, a high urinary recovery of FITC-HPαCD, FITC-HPβCD and FITC-HPγCD with 99.1 ± 2.6%, 103.4 ± 4.1% and 100 ± 6.7%, respectively, were observed. Considering low extinction coefficient of XITC and a higher dose of XITC-HPCDs might be needed in rats, XITC-HPβCD was chosen only for this trial. A similar tendency of urinary recovery (103.2 ± 5.4%, Figure 4d and Table S20) was also determined in the case of XITC-HPβCD. Indeed, urinary recovery of the given dose was almost completed at 6 to 9 h post-injection for FITC-HPβCD and FITC-HPγCD, which is in agreement with their short clearance half-life. These high urinary excretion rates indicated all the injected FITC-HPCDs and XITC-HPβCD are excreted into urine. However, only 40 to 60% of the injected doses were recovered for Fluorescein-HPCDs (Figure 4c, Figure S12 and Table S19). These results suggested that Fluorescein-HPCDs are not completely excreted through the kidneys, but also *via* other routes including metabolism by enzymes *in vivo*.[62] The excretion profiles of Fluorescein-HPCDs are consistent with their extremely short clearance half-life. Although

Fluorescein-HPCDs are stable under co-incubation with PLE *in vitro*, the aromatic carboxylic acid ester on Fluorescein-HPCDs is prone to hydrolysis in a complex environment *in vivo*.

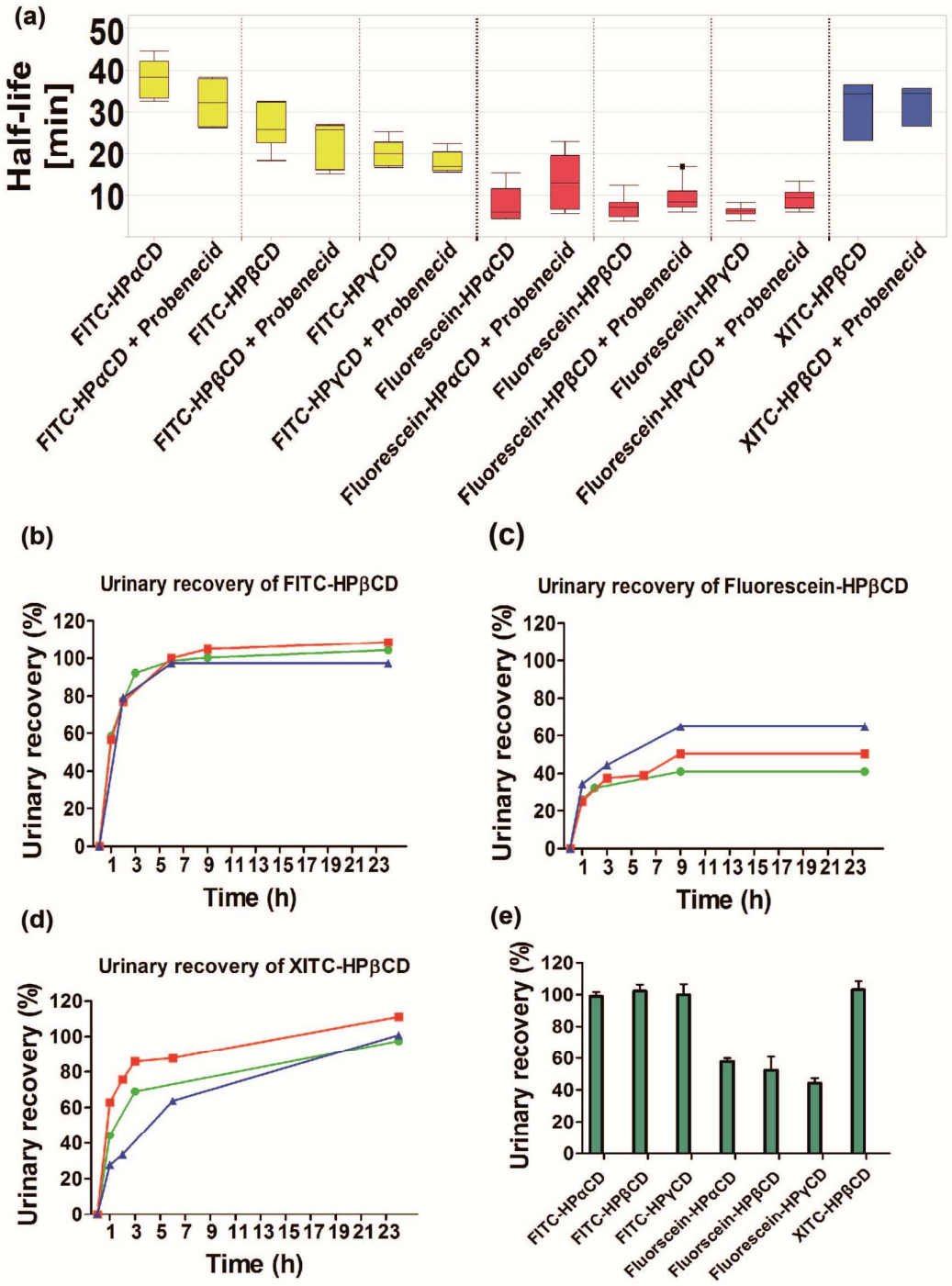


Figure 4. (**a**) Clearance half-life for each marker in the presence and absence of probenecid in rat models. (**b**) Urinary recovery for each marker in SD rats (n=3) after 24 h. Urinary recovery-time curves of FITC-HPβCD (**c**), Fluorescentin-HPβCD (**d**) and XITC-HPβCD (**e**) in SD rats (n=3) over a period of 24 h.

Metabolism studies

To evaluate whether these markers can be metabolized *in vivo*, urine samples were collected and investigated by HPLC. The HPLC results (Figure S14) indicate that metabolites were not formed. In order to better understand these results, we carried out an additional experiment by MALDI-TOF to confirm these markers in urine samples. The obtained MALDI-TOF data demonstrated that the mass distribution of FITC-HPβCD recovered from urine sample is the same as that of before injection (Figure 5c and S14). Therefore, we concluded that four substances, including FITC-HPαCD, FITC-HPβCD, FITC-HPγCD and XITC-HPβCD, have high urinary recoveries of nearly 100% of the injected doses and do not undergo metabolism *in vivo*. However, FITC-HPαCD and FITC-HPγCD are reabsorbed slightly in kidney tubule and XITC suffers from undesirable optical properties, thus a higher dose of XITC-HPCDs might be required for *in vivo* studies. It should be emphasized that neither premature deaths nor adverse clinical signs in behaviors, by measurement of body weight and food consumption of rats were observed during the whole experiments. Taken together, relying on the attractive features of FITC-HPβCD *in vivo* including completely and rapidly excreted through kidneys into urine, exclusively filtered via glomerulus, no reabsorption and secretion in kidney proximal

tubule, it is considered as a promising novel exogenous fluorescent GFR marker. In contrast, FITC-HPαCD and FITC-HPγCD have a potential to determine the capacity of reabsorption function in kidney tubules.

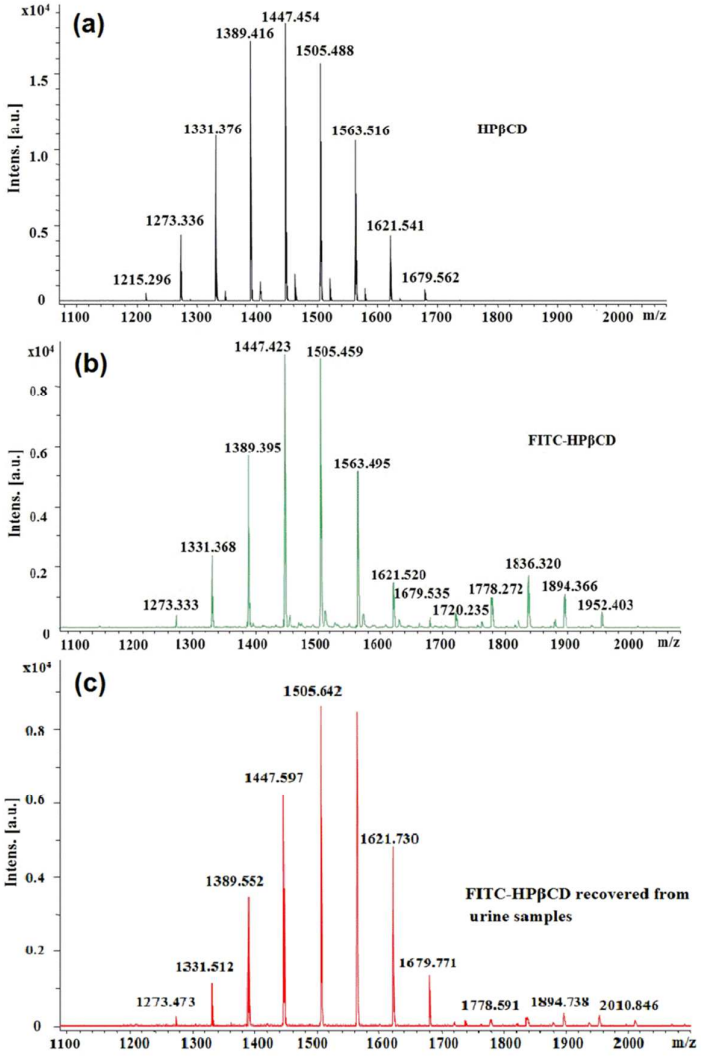


Figure 5. MALDI spectrum of (a) HPβCD, (b) FITC-HPβCD and (c) FITC-HPβCD recovered from urine samples in SD rats.

Conclusions

To summarize, by considering the basic principle of renally cleared drug design and the knowledge of CD-based drug delivery system, we developed a type of novel

fluorescent markers based on fluorophore labeled HPCDs. Through a rational screening approach, FITC-HPβCD is considered as the most promising exogenous marker for transcutaneous GFR measurements. This marker can be easily synthesized and exhibits desirable fluorescence properties. In *in vitro* experiments, low plasma protein binding, good stability in plasma and esterase, as well as no cytotoxicity were found. In rat models, a high urinary recovery of the given doses and no metabolism *in vivo* were observed. Noninvasive real-time monitoring of bolus clearance was determined in combination with a miniaturized electronic device for the transcutaneous fluorescence intensity detection in conscious rats. The results show no significant differences in clearance half-life of the markers in the absence and presence of probenecid treatment, so neither reabsorption nor secretion happened in kideny proximal tubule, demonstrated it is filtrated by glomerulus only. To the best of our knowledge, this is the first use of cyclodextrin derivatives as a backbone for developing a novel GFR marker. Our platform of novel fluorescent markers combined with transcutaneous fluorescent detection technique enables a rapid, robust and convenient monitoring of renal function without the need of time-consuming blood/urine sample preparation. Therefore in future this method allows the assessment of renal function in real-time and the evaluation of rapid changes in renal function, for example, in acute renal failure. Formal preclinical development studies are in progress. Finally, we noted that the development of near infrared transcutaneous devices and markers for deeper penetration depth will be an improvement for assessing kidney function.

Experimental Section

Materials

Reagents including fluorescent dyes (European Pharmacopoeia grade), anhydrous solvents (Purity ≥ 99.9%), and deuterated solvents (99.96 atom % D, contains 0.03 % (v/v) TMS) were purchased from Sigma Aldrich or Carl Roth. All other solvents were used as supplied (HPLC grade), without prior purification. Silica gel (Silicycle, 230-400 mesh) was used for column chromatography. 2-hydroxylpropyl-αCD, -βCD and -γCD have the degree of substitution (DS) 0.6, 1.0, and 0.6, respectively, and average molecular weight 1180, 1540, and 1580 Da, respectively. The catalog number of 2-hydroxylpropyl-αCD, -βCD and -γCD from Sigma Aldrich is 390690-25G, 389145-25G and 390704-25G, respectively. NMR spectra were recorded on a Bruker 300 MHz NMR instrument. Chemical shifts are reported in ppm relative to residual protic solvent resonances. Mestre Nova LITE v5.2.5-4119 software (Mestre lab Research S.L.) was used to analyze the NMR spectra. Matrix-assisted laser desorption/ionization time-of-flight (MALDI-TOF) analyses were collected on a Bruker microflex instrument. UV-vis and fluorescence spectra were acquired using a microplate reader (Tecan Infinite M200) and an Eppendorf biospectrometer kinetic device using quartz cuvettes (1 cm path length). HPLC analysis and separations were carried out on a Thermo scientific ultimate 3000 liquid chromatography using Ascentis® C18 columns. The pH of samples solution was tested by Mettler Toledo FiveEasy™ FE20pH bench meter. Dynamic light scattering studies were conducted using a Malvern Zetasizer Nano S90 equipment. IUPAC names of all compounds are

provided and were determined using CS ChemBioDraw Ultra 12.0. The transcutaneous devices are available from Mannheim Pharma & Diagnostics, Mannheim, Germany.

Synthesis

Synthesis of compound 2. A suspension of 2,2',4,4'-tetrahydroxybenzophenone (compound 1, 2.46 g, 10 mmol) in 16 mL H_2O was stirred and heated to 200 ℃ for 48 h. This reaction was accomplished in special pressure flask. The mixture was cooled to 60 °C, then it was poured into 60 ℃ hot water and kept stirring 20 min. The yellow residue was filtered and extensively washed by 60 ℃ hot water until no start material was left over (monitored by TLC, EtOAc/nHex, 1/1). 3, 6-dihydroxyxanthen-9-one (compound 2, 1.74 g) was obtained in a 76.3% yield. TLC (silica gel, EtOAc/nHex, 2/1) R_f= 0.28, ^{1}H NMR (300 MHz, DMSO-d_6) δ (ppm): 10.84 (s, 2H), 7.97 (d, J = 8.7 Hz, 2H), 6.84 (m, 4H). ^{13}C NMR (75 MHz, DMSO-d_6) δ (ppm): 173.87, 163.32, 157.43, 127.72, 113.96, 113.61, 102.05. LRMS (m/z): calcd: 228.05, found: 228.13.

Synthesis of compound 3. To a solution of 3, 6-dihydroxyxanthen-9-one (compound 2, 1.70 g, 7.45 mmol) and tert-butylchlorodimethyl silane (TBDMS-Cl, 6.90 g, 45.78 mmol) in DMF (30 mL), imidazole (5.20 g, 76.30 mmol) was added. The mixture was stirred at room temperature 12 h. The reaction was diluted by toluene (75 mL) and then extensively washed and extracted by water. The product was recrystallized from ethanol to recieve the di-protected product (compound 3, 3.12 g) with a yield of 91%. TLC (silica gel, EtOAc/nHex, 2/1) R_f = 0.9, ^{1}H NMR (300 MHz, DMSO-d_6) δ (ppm): 7.94 (d, J = 9.1 Hz, 2H), 6.80 (m, 4H), 1.23 (s, 18H), 0.84 (s, 12H). LRMS (m/z):

calcd: 456.22, found: 456.91. The characterization data is comparable with the previous reports.[38]

Synthesis of compound 4. To a solution of xanthone diTBDMS ether (compound 3, 3.10 g, 6.78 mmol) in anhydrous THF was added phenylmagnesium bromide derivative (25 mL, 0.50 mol/mL in THF). This mixture was stirred under gas N_2 protection for 4 h. The reaction was quenched by adding 10 mL of 2 N HCl (aq) and stirred for 30 min, then 5 mL NaOH (3 mol/mL) was added dropwise to rise the pH of the mixture to 7.5 at ice bath. The resulting yellow precipitate was filtrated, washed with a small volume of distilled THF and dried in vacuum, to yield a product (compound 4, 1.81 g, yield 87.6%). Further purification by silica gel column chromatography was done if required. LRMS (m/z): calcd: 303.09, found: 303.25.

Synthesis of compound XITC. Thiophosgene (6 mL, 78 mmol) was dissolved in anhydrous CH_2Cl_2 (10 mL).This mixture was chilled to 0 ℃ in an ice bath. Product amine (compound 4, 1.80 g) was dissolved in anhydrous CH_2Cl_2 and added slowly in sequence. This mixture was allowed to warm to room temperature over 3 h. The mixture was concentrated under reduced vacuum and extensively washed by acetone to obtain 9-(4-isothiocyanatophenyl)-9H-xanthene-3, 6-diol (compound XITC). TLC (silica gel, MeOH/ EtOAc, 1/9) R_f= 0.5, ^{1}H NMR (300 MHz, DMSO-d_6) δ (ppm): 8.13 (d, J =9, 1H), 7.71(d, J =9, 1H), 7.63 (s, 2H), 7.48 (m, 4H), 7.02 (d, J =9, 2H). LRMS (m/z): calcd: 345.05.22, found: 345.57.

General procedures for the synthesis of FITC-HPαCD, FITC-HPβCD and FITC-HPγCD. To a solution of (2-hydroxypropyl)-α-cyclodextrin (HPαCD, 800 mg)

in DMF (8 mL), NaH (400 mg, 10 mmol, 60% susp.) was added slowly and stirred at room temperature. The reaction was stirred at 45 °C for 30 min. Afterwards, FITC (100 mg, 0.26 mmol) was added and the mixture was stirred at 45 °C for another 30 min and then kept at room temperature in the dark for 18 h. The red solution was cooled in an ice bath, saturated NH_4Cl solution was added then to adjust pH near 10. Then using 5 % acetic acid was added dropwise to obtain a pH of 7.5. The solvent was concentrated under reduced pressure in a rotary evaporator (bath temperature 45 °C). The crude product was washed by acetone two times (300 mL in each time) and filtered; the orange remains were purified by gel silica chromatographic column with gradient eluent (EtOAc, MeOH/EtOAc (1/2) and MeOH/H_2O (8/2)). The weight amount of silica gel per gram of crude products is 210 g. The eluent was concentrated under vacuum. To transfer this into a more handable form, the material is dissolved in 100 mL H_2O at room tempertaure, filtered, and freeze-dried to yield a yellow solid FITC-HPαCD. According to the same procedure of FITC-HPαCD, FITC-HPβCD and FITC-HPγCD were obtained. ^{1}H-NMR; ^{13}C-NMR and Mass data are available in supporting information.

General procedures for the synthesis of Fluorescein-HPαCD, Fluorescein-HPβCD and Fluorescein-HPγCD. To a solution of (2-hydroxypropyl)-α-cyclodextrin (HPαCD, 2.0 g) and fluorescein (300 mg, 0.90 mmol) in DMF (10 mL), EDC (300 mg, 1.56 mmol) and DMAP (27 mg, 0.22 mmol) was added. The reaction was stirred without light at room temperature for 18 h. The resulting solution was concentrated under reduced pressure. The residue was purified by a gel silica chromatographic column with

gradient eluent (EtOAc, MeOH/EtOAc (1/2) and MeOH/H_2O (8/2)). The weight amount of silica gel per gram of crude products is 210 g. The eluent was collected and concentrated under vacuum. This product was dissolved in water and freeze dried to yield a red solid Fluorescein-HPαCD. According to the same procedure of Fluorescein-HPαCD, Fluorescein-HPβCD and Fluorescein-HPγCD were obtained. ^{1}H-NMR; ^{13}C-NMR and Mass data are available in supporting information.

General procedures for the synthesis of XITC-HPαCD, XITC-HPβCD and XITC-HPγCD. To a solution of (2-hydroxypropyl)-α-cyclodextrin (HPαCD, 1.0 g) in DMF (8 mL), NaH (500 mg, 12.5 mmol, 60% susp.) was added slowly and stirred at room temperature. The reaction was stirred at 45 ℃ for 30 min. Afterwards, XITC (100 mg, 0.29 mmol) was added and the mixture was stirred at 45 ℃ for another 30 min and then kept at room temperature in the dark for 18 h. The red solution was cooled in an ice bath and saturated NH_4Cl solution was added to adjust pH near 10. Then using 5 % acetic acid was added drop wise to obtain a pH of 7.5. The solvent was concentrated under reduced pressure in a rotary evaporator (bath temperature 45 ℃). The crude product was washed by acetone two times (300 mL in each time) and filtered; the orange remains were purified by a gel silica chromatographic column with gradient eluent (EtOAc, MeOH/EtOAc (1/2) and MeOH/H_2O (8/2)). The weight amount of silica gel per gram of crude products is 210 g. The eluent was concentrated under vacuum. To transfer this into a more handable form, the material is dissolved in 100 mL H_2O at room tempertaure, filtered, and freeze-dried to yield a yellow solid XITC-HPαCD. According to the same procedure of XITC-HPαCD, XITC-HPβCD

and XITC-HPγCD were obtained. ^{1}H-NMR; ^{13}C-NMR and Mass data are available in supporting information.

Optical properties characterization

Stock solutions of all the compounds were prepared and stored at -20 °C. All the spectroscopic measurements were conducted in phosphate buffered saline (PBS) and/or mixed with rat plasma for intended use. UV-vis and fluorescence spectra were acquired using a microplate reader (Tecan Infinite M200) or an Eppendorf biospectrometer kinetic device. All measurements were conducted at 25 °C. Extinction coefficient of fluorophore was determined by using 20 μM solutions in aqueous buffer and calculated based on the Lambert- Beer law.

Degree of labeling

The degree of labeling (DOL) is defined as the average number of dye molecules coupled to CDs derivatives.[39] The DOL can be determined from the absorption spectrum of a marker against the corresponding free dye standard solution of known concentration.[45] The calibration curves were performed in a series of known concentrations of free dyes (Table S4 and Table S6). Their corresponding UV absorption was measured and calibration curves were performed based on the UV absorption values (Figure S3 and S4). Subsequently, absorbances of FITC-HPCDs, Fluorescein-HPCDs, XITC-HPCDs with corresponding concentration were measured, and their degree of labeling was calculated based on the calibration curves and the equation 1.

$$\mathrm{DOL}= \frac{C1}{MW1} \times \frac{(MW2 + MW1 \times DOL)}{C2} \quad (1)$$

Where C1 is the concentration of the dye labeled in HPCDs, MW1 is the molecular weight of dye, MW2 is the average molecular weight of HPCD, C2 is the concentration of markers (dye conjugated with HPCD), DOL is the value of degree of labeling.

Dynamic light scattering analysis

Dynamic light scattering (DLS) studies were conducted on aqueous solutions of FITC-HPCDs and Fluorescein-HPCDs. The samples were prepared at the desired concentration (3 mM) and filtered through a sterile 0.22 μm filter before analysis. The Zetasizer Nano S90 uses a 633 nm helium-neon laser. The measurements were carried out in quadratic cells and analyzed the scattered light at an angle of 90° at a controlled temperature (25 °C). All samples were analyzed in triplicate using the DTS Software from Malvern Instruments. The intensity of scattering of a particle is assumed to be proportional to the sixth power of its diameter. The apparent hydrodynamic radius was calculated according to the Stokes-Einstein equation.

Plasma protein binding

A marker-protein stock solution was prepared by incubating 2 mL of the corresponding marker (1 mg/mL in PBS) with 8 mL Sprague Dawley rat plasma in Li-Heparin (Innovative Research, Novi, MI, USA) at 37 °C, while 2 mL PBS was incubated with 8 mL rat plasma as control. Plasma protein binding measurements were performed by equilibrium dialysis of PBS against marker-protein stock solution (or control stock solution) using a two-chamber dialysis set-up. After 24 h the absorption of each of the markers in PBS and plasma were determined in three

independent measurements by both absorption spectroscopy and fluorescence spectroscopy in a microplate reader. The concentrations of each of the markers were calculated on the basis of the corresponding molar absorption coefficients.[52-54] All experiments were performed in triplicate. PPB of each of the markers in percent [%] was determined by averaging three independent measurements and following the equation of Lambert Beer law: PPB= [A(plasma) - A(PBS)]/[A(plasma) + A(PBS)] x 100% (2), where A is corresponding to UV absorption.

Stability studies in esterase and plasma

The mixtures of plasma or porcine liver esterase (PLE, 20 mg/mL, 150 unit/mL) with each of the markers (50 mg/mL in sodium phosphate buffer solution, pH 7.5-8.0) were incubated at 37 °C for 24 h. After incubation they are filtered *via* sterile syringe filter with a membrane pore size of 0.22 μm and transferred to a proper vial. Samples of three control groups such as plasma, native fluorophore and the corresponding marker were prepared according to the same procedure. Plasma and esterase enzymatic degradation were monitored by injecting 30 μL of each sample into HPLC. The gradient program A is described in Table S1.

Cytotoxicity analysis

The cytotoxicity of FITC-HPβCD and Fluorescein-HPCDs was evaluated by using standard (4,5-dimethyl-2-thiazolyl)-2,5-diphenyltetrazolium bromide (MTT) assay in a 96-well plate set up to assess the viability of cultured cells. Two conditionally immortalized human proximal tubule cell lines (ciPTEC),[58] which overexpress either the organic anion transporter ciPTEC-OAT1 or ciPTEC-OAT3 were used as in vitro

models. Cells were cultured as follows: densities of 55000 cells p/cm^2 for ciPTEC-OAT1 and 83000 cells p/cm^2 for ciPTEC-OAT3 were used. Cells were grown at 33 °C for 24 h and matured for 7 days at 37 °C prior to all assays. Cells were incubated for 3 h at 37 °C with various concentrations of FITC-HPβCD and Fluorescein-HPCDs (0.006, 0.013, 0.025, 0.05, 0.1 and 0.2 mg/mL) in Hank's balanced salt solution (HBSS: an isotonic solution used for washing and incubating cells; Gibco). After the treatment cells were washed 2 times with HBSS and incubated with 5 mg/mL MTT, freshly prepared in HBSS for 3 h. After MTT incubation cells were washed 2 times with HBSS and 100 µL of dimethyl sulfoxide (DMSO) was added to the wells (in order to dissolve MTT crystals). The plates were then placed in an orbital shaker for a minimum of 30 min and subsequently absorbance was measured at 570 nm. The cell viability was calculated as the ratio of the absorbance of the sample to that of the control cells and expressed as a percentage. All experiments were performed in triplicate.

Principle and Method of transcutaneous measurement

The transcutaneous assessment of renal function is based on the measurement of the fluorescence signal of a marker through the skin. Briefly, a miniaturized transcutaneous device contains two light emitting diodes (LEDs) and one photodiode (Figure S1). The LEDs can blink every few seconds to excite a fluorescent marker using excitation wavelength at 480 nm. The fluorescent signal will be recorded by detecting the emission wavelength at 520 nm. Data are stored in the device and can be read out after measurement.[22, 27] The clearance half-life of fluorescent markers was

calculated by software, which was developed by the Institute of Medical Technology of the University of Heidelberg.[63] For this a 3-exponential function was fitted to the measured elimination curve, the peak of the curve was supposed to be 100%. Also a 1-exponential function was applied from 50% to 15% of the peak height.

Sprague Dawley rats were anesthetized for a short period with Isoflurane (Forene®, AbbVie, Illinois, USA; Dosage: 5 %; Flow(O_2): 5 L/min) in order to fix a transcutaneous device the back of rats and inject a fluorescent marker solution. The back of the animals was depilated with an electric shaver and depilation creme (Veet®, Reckitt-Benckiser, Slough, UK) to avoid auto-fluorescence of the fur. After a baseline measurement for around 5 min, a fluorescent marker in saline (DeltaSelect, GmbH, Rimbach, Germany) was injected as a bolus by tail vein injection. The dosages of fluorescent markers are depended on fluorescent quantum yield and degree of labeling of each marker (FITC-HPCDs: 50 mg/kg, Fluorescein-HPCDs: 50 mg/kg, XITC-HPβCD: 180 mg/kg,). Rats were conscious during the measurement and housed in separate cages. The devices were removed and the data were read out after 120 min transcutaneous measurement. In probenecid inhibition studies, Sprague Dawley rats were treated in the same manner as described above. The rats group received 50 mg/kg probenecid intraperitoneally injection 30 min prior to injection of the test markers. Conversion of clearance half-life into GFR can be performed if needed. The method is based on our previous studies.[26, 28] All experiments were conducted in accordance with the German Animal Protection Law and approved by the local authority (Regierungspräsidium Nordbaden, Karlsruhe Germany in

agreement with EU guideline 2010/63/EU).

Urinary recovery of injected doses

Recovery of the injected dose in urine studies were conducted in conscious SD rats. The corresponding test markers with corresponding dosage (5 mg/100g b.w.) were administered by tail vein injection. Urine was collected using metabolic cages in intervals of 1, 2, 3, 6, 9, 24 h after intravenous injection of markers into rats. The urine samples were centrifuged for 8 min at 13000 ×g and then filtered by 0.22 μm syringe filter. A series of working solution of each marker with concentrations between 0.02 mg/mL and 2 mg/mL were prepared. Appropriate volumes of the working solutions were added to blank urine and fluorescent intensity of those mixtures were measured in order to obtain an external calibration curve. Quantification of each of the markers in urine at each time point was performed via HPLC analysis and fluorescence intensity detection. The concentration in urine at each time point was calculated based on the external calibration standards curve between fluorescence intensity and the concentration of each of the markers. The samples handling and measuring procedures were similar with that described for plasma protein binding and labeling degree measurement.

Determination of urinary metabolites

Urine samples were collected and stored at -20 °C until analysis. Urine samples were centrifuged for 8 min at 13000×g and then filtered by 0.22 μm syringe filter. The filtered urine samples were determined by HPLC. The gradient program B is described in Table S1. Select portions of the eluent were collected based on the

processed signal and measured by a mass spectrometer.

Supporting Information

The Supporting Information is available free of charge on the

Supplementary figures (UV-vis and fluorescent spectra, NMR and Mass spectra, DLS, Plasma protein binding and urinary recovery data)

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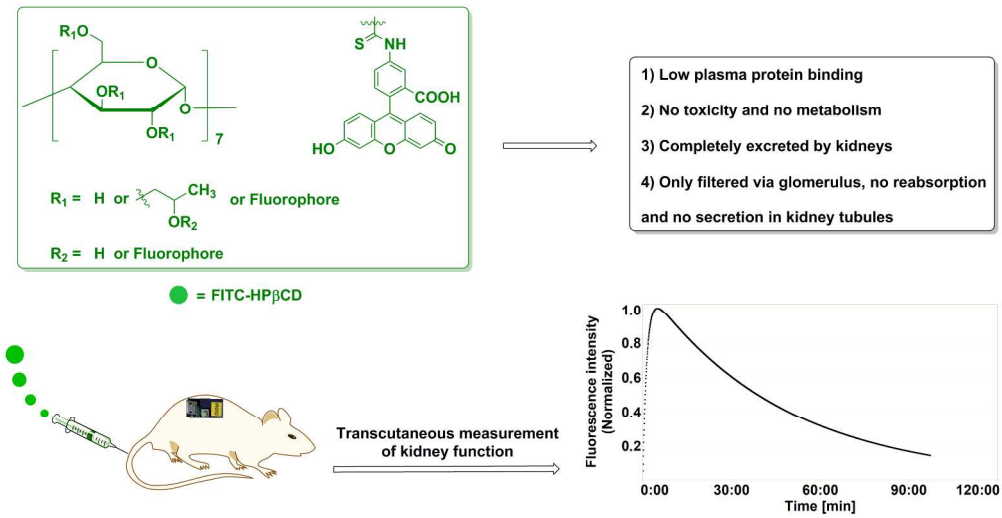

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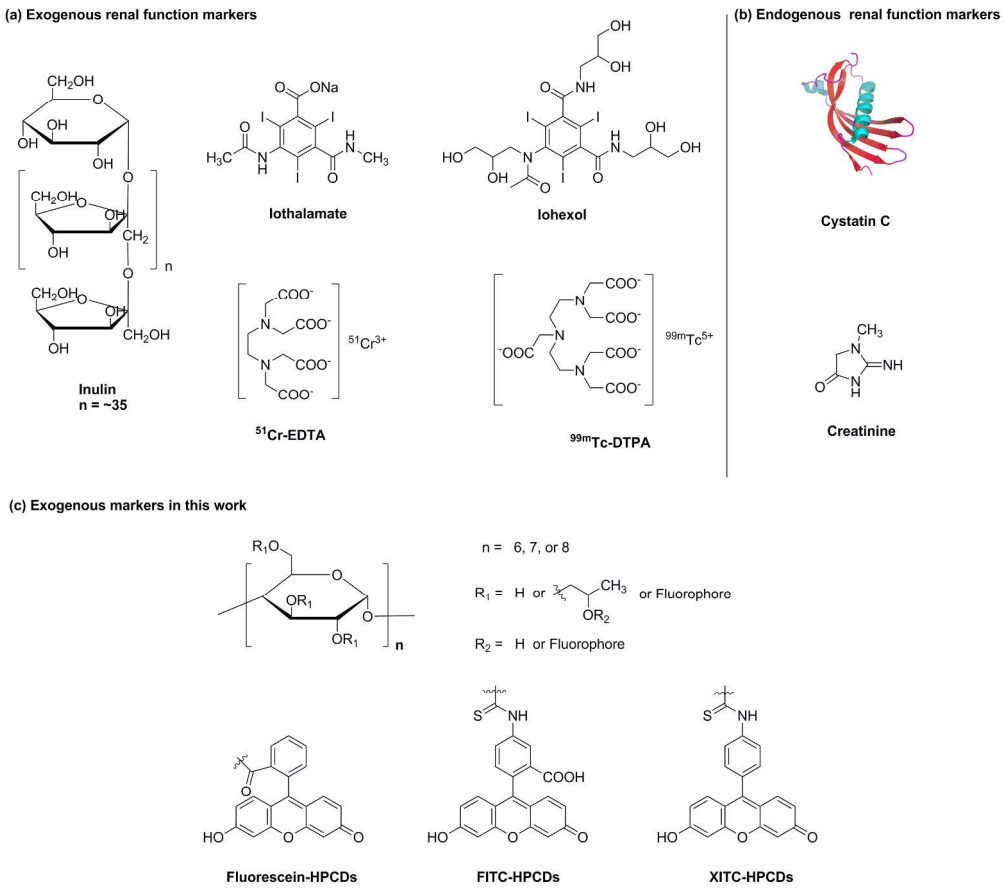

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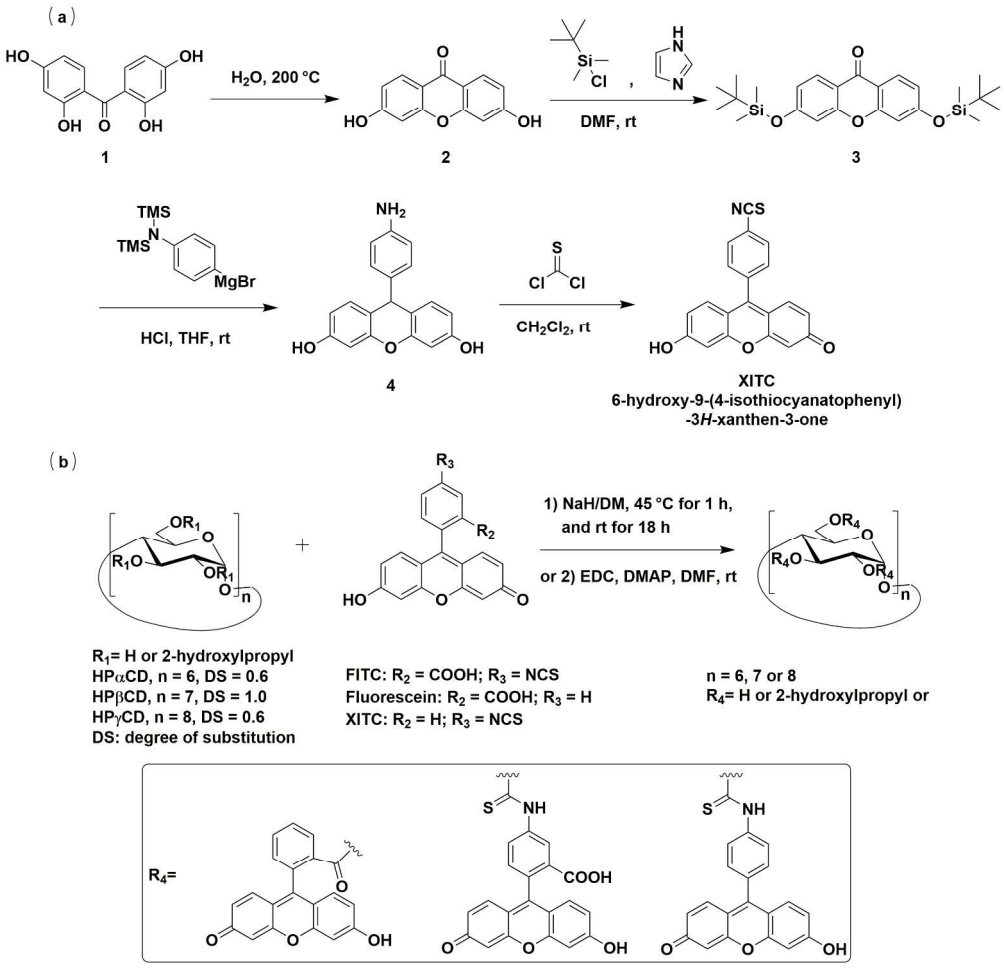

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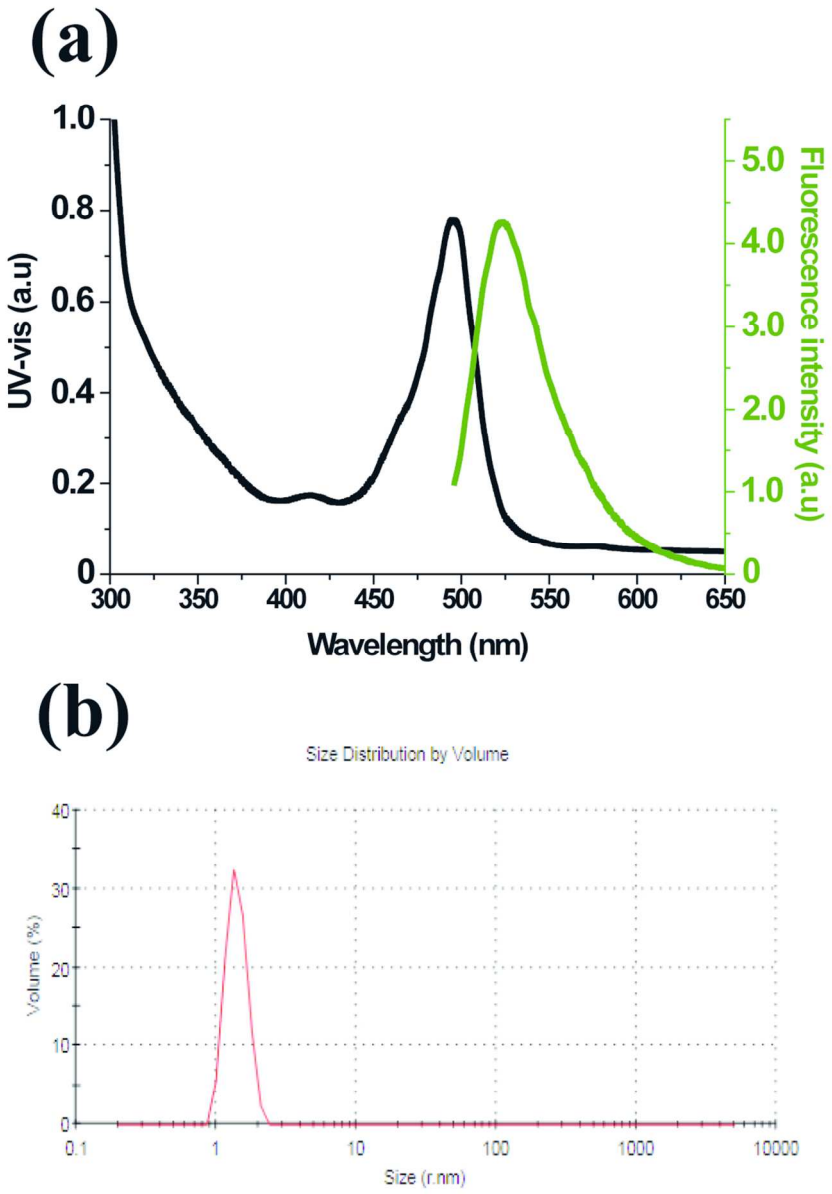

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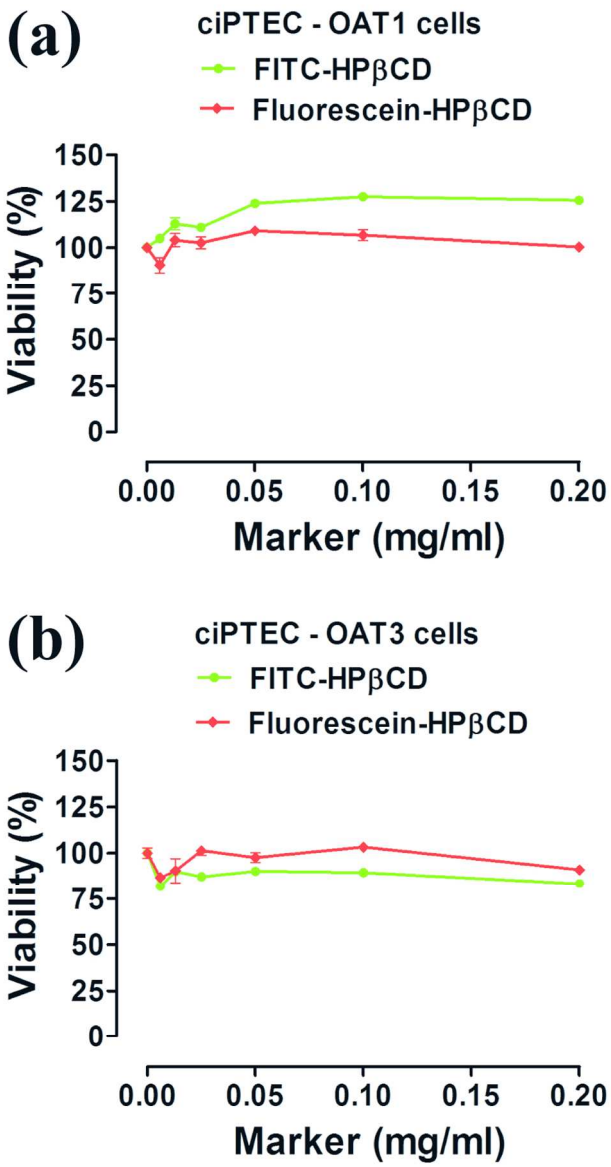

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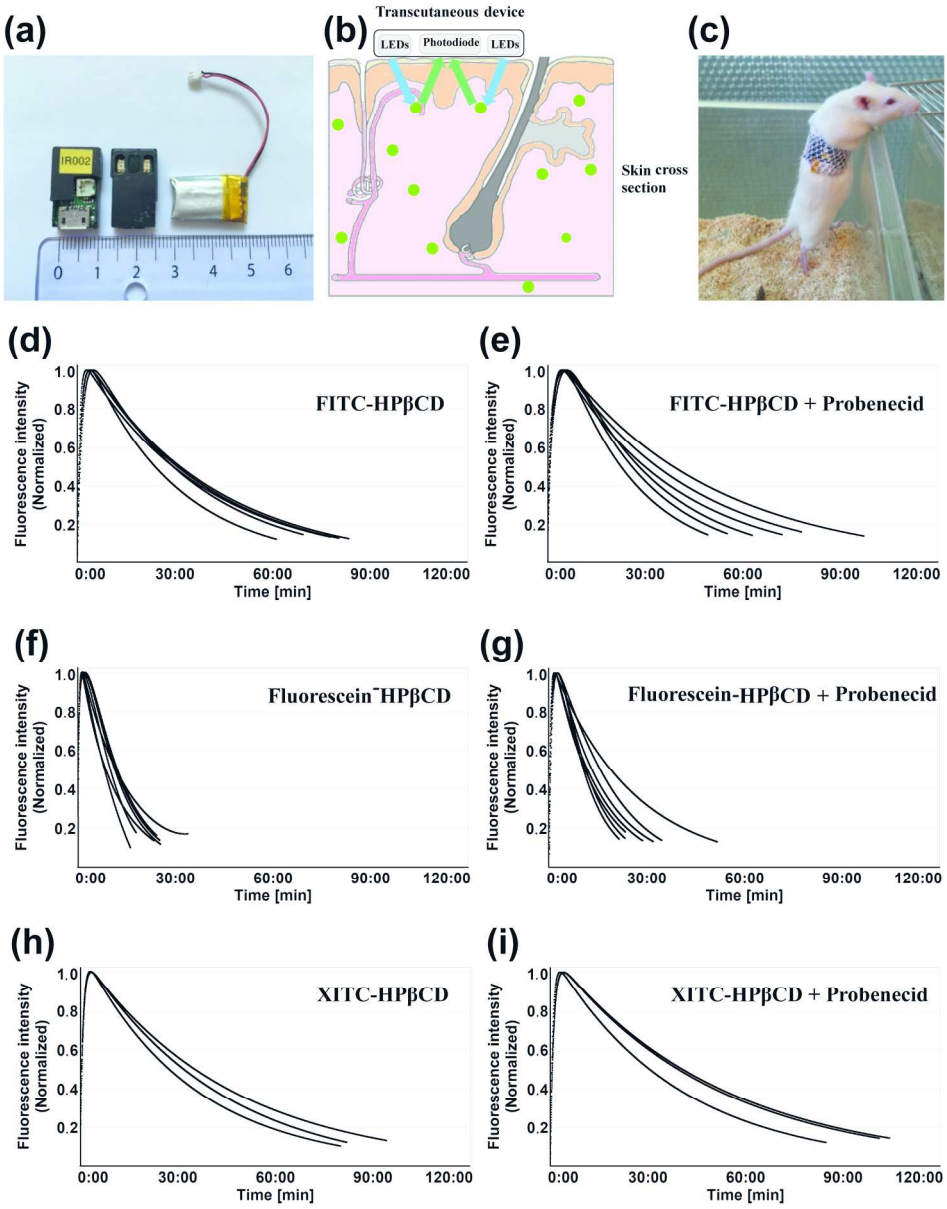

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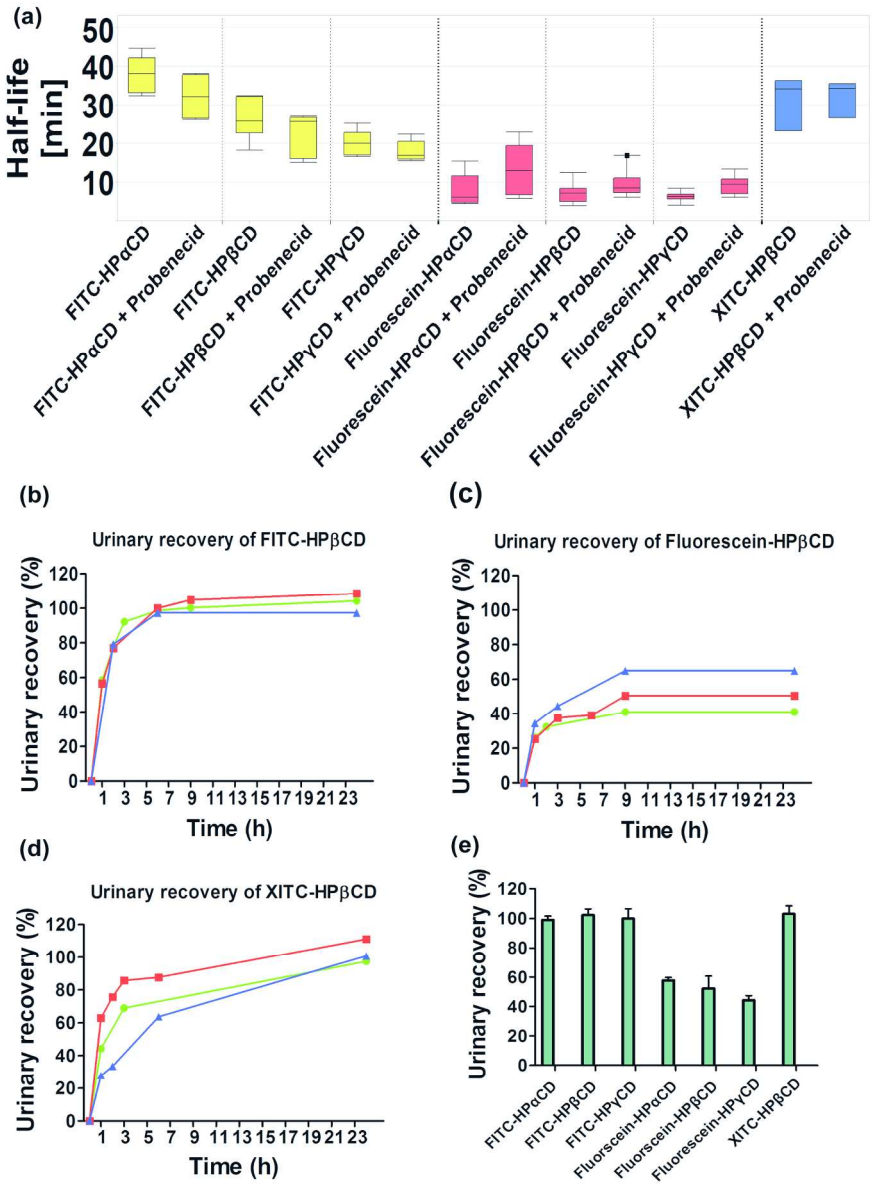

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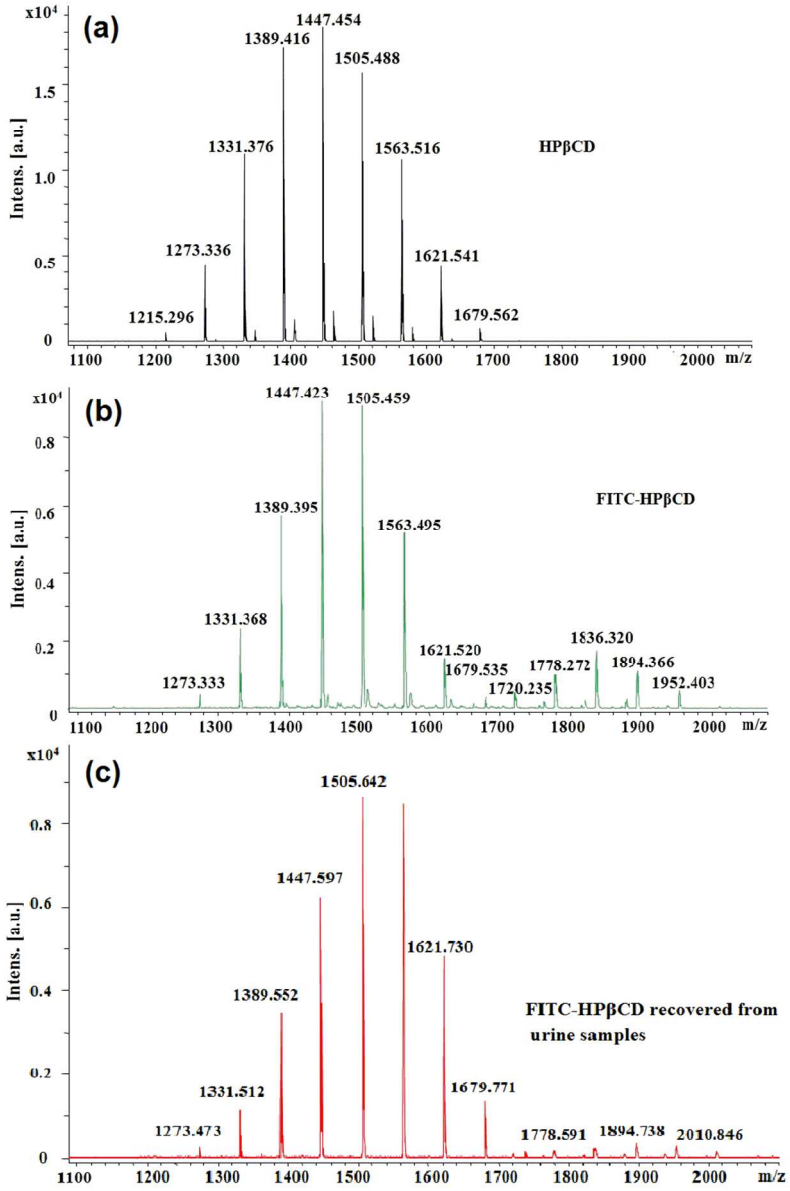

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