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Investigation of the Small Size of Nanobodies for a Sensitive Fluorescence Polarization Immunoassay for Small Molecules: 3-Phenoxybenzoic Acid, an Exposure Biomarker of Pyrethroid Insecticides as a Model

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Supporting Information

ABSTRACT: Limited reports on the use of nanobodies (Nbs) in fluorescence polarization immunoassay (FPIA) aroused us to explore if the small size of Nbs is a drawback for the development of sensitive FPIA to small molecular compounds, particularly since FPIA is a technology strongly dependent on molecular weight. In the present work, three different molecular weight Nbs against 3-phenoxybenzoic acid (3-PBA), an exposure biomarker of pyrethroid insecticides, including bare Nbs (15 kDa), Nbs-Avidin (Nbs-AV, 60 kDa), and Nbs-Alkaline phosphatase (Nbs-AP, 130 kDa) were specifically generated to cover distinct regions on the polarization and molecular weight relationship curve for a fluorescein tracer. In competitive FPIA, similar half-maximal inhibitory concentrations (IC_{50}) of 3-PBA of 16.4, 12.2, and 14.8 ng mL^{-1} were obtained for Nbs, Nbs-AV, and Nbs-AP, respectively, indicating that the size of Nbs in the range tested had no significant effect on the sensitivity of the resulting competitive FPIA. An IC_{50} of 20.2 ng mL^{-1} for an anti-3-PBA polyconal antibody based FPIA further demonstrated the performance of Nbs, which was comparable to that of traditional antibodies in FPIA. Spike-recovery studies showed good and reproducible recovery of 3-PBA in urine samples, demonstrating the applicability of Nb-based FPIA. Overall, our results show that Nb-based FPIA achieves sensitivity levels of FPIA based on conventional antibodies and further indicate that Nb absolutely meets the sensitivity requirement of FPIA.

KEYWORDS: *fluorescence polarization immunoassay, nanobody, insecticide, 3-phenoxybenzoic acid, fluorescein*

1. INTRODUCTION

Nanobodies (Nbs), also referred to as single domain antibodies, are a recombinant form of heavy-chain-only antibodies, have emerged as a versatile alternative for conventional IgGs since they were first reported in 1993.[1] Although Nbs possess only a single variable domain, their affinity and specificity for the target molecule compares favorably with traditional IgGs.[2] Their small size, high conformational stability, and ease of recombinant modification and production not only trigger the current bloom of therapeutic applications of Nbs but also create and boost novel immunoassays.[3]

The small size (≈15 kDa; ≈4 nm × 2.5 nm × 3 nm), a canonical representation of Nbs, endows advantages in different immuno-based applications, such as in vivo molecular imaging,[4,5] biosensor development and homogeneous Förster resonance energy transfer (FRET)-based immunoassays.[6,7] In tumor imaging, the small size of Nbs is advantageous in terms of tumor penetration, rapid biodistribution and tumor labeling, which results in short time imaging and high-contrast images.[5,8] In addition, the reduced size contributes to higher antibody-coating density on the sensor surface, which was shown to improve the biosensor performance.[6] In FRET-based immunoassays, the small Nb size has been shown to reduce the distance between two fluorophores, thus resulting in higher FRET effciency.[7] The tiny size renders Nbs, not just alternatives to traditional antibodies, but in some cases, the outstanding property of Nbs allows higher performances that cannot be accomplished with traditional antibodies.

Recently, Nbs have been used in a plethora of assay formats,[6,7,9,10] yet the use of Nbs in fluorescence polarization immunoassays (FPIA) is rare. Thus, an obvious question arises: is there any limitation of Nb use in FPIA? Since FPIA is a molecular mass sensitive analytical technique, without doubt is, the molecular size of Nbs is the first and most probable suspect. This inspired us to investigate whether the small size

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of Nbs is a hindrance in achieving high-performance FPIA, i.e., high sensitivity.

FPIA, a homogeneous assay technique, is mainly used for the rapid monitoring of low-molecular-weight compounds, including drugs in clinical diagnostics, pollutants, and toxins in environmental and food control.[11−14] FPIA offers significant advantages in terms of being separation free with ease of automation, resulting in high-throughput and fast processing. The steady-state fluorescence polarization signal (P) depends on the excited state lifetime τ and the Debye rotational relaxation time ρ of a fluorescently labeled molecule and can be expressed by the well-known Perrin equation: $\frac{1}{P} - \frac{1}{3} = \left(\frac{1}{P_0} - \frac{1}{3}\right)\left(1 + \frac{3\tau}{\rho}\right)$, where P_0 is the intrinsic polarization.[13,15] For a spherical molecule, the Debye rotational relaxation time ρ can be formulated as: $\rho = \frac{3\eta V}{RT}$, where η is the viscosity, V is the molar volume of the rotating molecule, R is the gas constant, and T is the absolute temperature.[11,14] In a constant solution system (constant η, R, and T) with a fixed fluorophore (constant τ), the P is proportional to the molecular volume or the molecular mass. That is to say, the polarization of a rotating fluorophore is low when it is attached to a small species, but is high with a large one. In a competitive FPIA, the analyte competes with a small fluorescent-labeled antigen (tracer) for the limited binding site of a specific antibody, resulting in a decrease in the degree of light polarization value.[16,17]

To get high sensitivities, a significant difference between the polarization value of the bound and free tracers is required. However, a molecule with a molecular weight of 15 kDa appears not to get a saturated polarization value according to previous studies.[18] Thus, when a Nb is used in FPIA, the contribution of the polarization difference to the sensitivity is not clear, since the sensitivity of a competitive immunoassay system is intricately determined by the concentration of the competitive antigen and/or antibody, the heterogeneity of the antigen, the affinity of the antibody, the properties of signal tags, etc.[19,20] An anchor protein module concept was used to increase the size of aptamer receptors in the fluorescence polarization aptamer assay for ochratoxin A with an enhancement of assay sensitivity.[21]

On these bases, three different molecular weight Nbs were developed to make a sensitivity comparison of their corresponding competitive FPIAs. The molecular weights of three selected Nbs were specifically chosen at three representative points of the polarization−molecular weight relationship curve for a fluorescein tracer,[18] which were at the fast-rising point of that curve (15 kDa), approaching the saturation point (60 kDa), and the saturation point (130 kDa), respectively. The three Nbs against 3-phenoxybenzoic acid (3-PBA) were generated by recombinant fusion technology, including bare Nbs (15 kDa), Nbs-Avidin (Nbs-AV, 60 kDa), and Nbs-alkaline phosphatase (Nbs-AP, 130 kDa). The use of recombinant fusion protein alleviates the need to prepare chemical conjugates via chemical labeling with different substances (e.g., proteins or metal nanoparticles), which sometimes damages the activity of the antibody and may result in highly heterogeneous conjugates due to the difficulty in controlling the binding ratio. The performance of the Nbs in competitive FPIA by quantitative detection of 3-PBA, which is considered as a metabolic biomarker of many pyrethroid insecticides[22] (Figure 1A), was evaluated in detail. Finally, a Nb-based FPIA was used to analyze 3-PBA in urine samples.

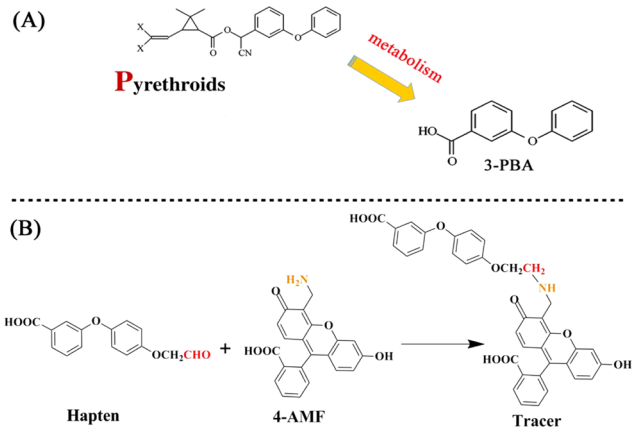

Figure 1. (A) Structures of pyrethroid and its metabolite 3-PBA and (B) Synthetic scheme of tracer antigen conjugate synthesis using a 3-PBA hapten and 4′-(aminomethyl)fluorescein (4-AMF).

2. MATERIALS AND METHODS

2.1. Chemicals. DNA polymerase, nicking enzyme, T4 DNA ligase, and 10× CutSmart buffer were obtained from New England Biolabs (Beverly, MA). Bacterial protein extraction reagent (B-PER), NuPAGE Bis−Tris gel, and HisPur Ni-NTA resin were purchased from Thermo Fisher Scientific (Rockford, IL). The pET 22b (+) vector containing the Rhizavidin (RZavidin) fragment and the pecan45 vector containing the alkaline phosphatase (AP) fragment were generously provided by Dr. Ellen R. Goldman (Naval Research Laboratory, DC), and 3-phenoxybenzoic acid (3-PBA) was purchased from Sigma-Aldrich (St. Louis, MO). The hapten 3-(4-methoxyphenoxy)-benzoic acid was previously synthesized in our laboratory at UC Davis (University of California Davis, CA), and 4′-(aminomethyl)fluorescein (AMF) was obtained from AAT Bioquest, Inc. (Sunnyvale, CA). Polyclonal antibodies and nanobody genes were previously prepared in our lab.[22,23]

2.2. Generation of Nbs. Recombinant plasmids encoding the bare Nbs and Nbs-AV and Nbs-AP fusion proteins with 6× His tags at the C-terminus were constructed, respectively, using classical gene recombination technology including gene amplification, enzyme digestion, and ligation (details in the Supporting Information). Few single colonies of the transformed cells were picked and sequenced at the UC Davis DNA Sequencing Facility. The target plasmid was transformed into *Escherichia coli* BL21 (DE3) plysS cells to induce the protein expression in an auto-induction media. The cells containing target fusion protein were lysed by using the bacterial protein extraction reagent kit (B-PER) followed by purification on a 1 mL Ni-NTA resin column. The size and purity of those Nbs were determined by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) (Figure 2).

2.3. Synthesis of the Tracer Antigen. The tracer antigen conjugate was synthesized by formation of a Schiff base by reacting the amino group of fluorescein with the aldehyde group of the hapten (Figure 1B). Briefly, 11 mg of 3-PBA hapten was dissolved in 1 mL of *N*,*N*-dimethylformamide and mixed with 4 mg of 4′-(Aminomethyl)-fluorescein (4-AMF) with gentle stirring for 1 h at room temperature (RT) in the dark. Then, 10 μL of 5 M cyanoborohydride in 1 N NaOH was added to the mixture for an additional 4 h stirring in the dark at RT.

The resulting yellow solution was purified by thin-layer chromatography (TLC) with a mobile phase of CH_2Cl_2/CH_3OH (3:2, v/v). The band with a retention factor (R_f) of 0.55 was collected and dissolved in methanol. The tracer antigen conjugate was

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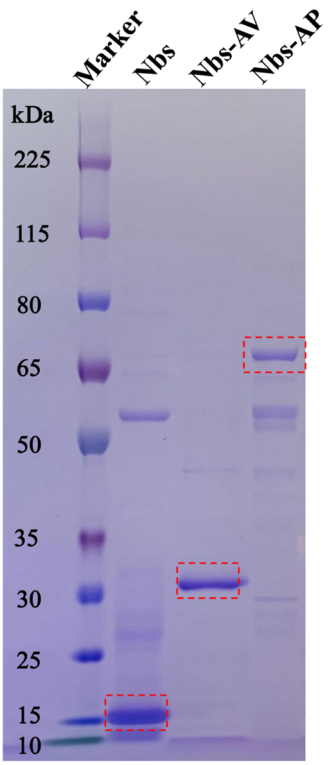

Figure 2. SDS-PAGE analysis of the Nbs and Nbs-AV and Nbs-AP proteins. Red dashed squares show the target band of each antibody. Blots were stained with SYPRO Ruby protein-gel stain.

characterized by mass spectrometry and the fluorescence polarization value test using a specific anti-3-PBA polyclonal antibody.

2.4. FPIA Protocols. Competitive FPIA was carried out with 3-PBA standard solutions or spiked samples in the presence of a tracer antigen conjugate and anti-3-PBA Nbs at optimized concentrations. Briefly, 70 μL of the tracer antigen conjugate, 70 μL of the antibody solution, and 70 μL of the sample solution were mixed and incubated in a 96-well black polystyrene microplate for 15 min. A blank control was also measured using borate buffer (BB, 0.05 M, pH 8.0). The fluorescence polarization (FP) value was measured in the fluorescence polarization mode at λ_{ex} = 485 nm and λ_{em} = 530 nm by a TECAN Infinite M1000 Pro multimode microplate reader (Hombrechtikon, Switzerland).

The standard inhibition curve with the *x*-axis being 3-PBA concentration and the *y*-axis being the normalized FP value (mP/mP_0, where mP is the FP value in the presence of 3-PBA and mP_0 is the FP value of the control) was plotted in Origin 8.5 software (OriginLab, MA) with a four-parameter logistic equation for line fitting

$$Y = A_2 + (A_1 - A_2)/[1 + (X/X_0)^P]$$

where Y represents the binding rate (mP/mP_0), X is the concentration of 3-PBA, A_1 and A_2 are the binding rates at saturated analyte concentration and zero analyte concentration, X_0 is the concentration of 3-PBA at 50% binding rate (EC_{50}), and P is the slope at the EC_{50} point.

2.5. Analysis of Urine Samples. Urine samples collected from healthy volunteers of our laboratory were used to test the recovery. Urine samples free of 3-PBA certified by liquid chromatography–mass spectrometry (LC–MS) were spiked with 3-PBA at concentrations of 100 and 400 ng mL^{-1}, respectively. After 20-fold dilution with BB, the solutions were analyzed by the Nb-based FPIA. For method comparison purposes, 50 μL of these samples were mixed with 50 μL of 200 nM 12-(3-cyclohexyl-ureido)-dodecanoic acid in methanol prior to LC–MS analysis for 3-PBA. Quantification was performed using Masslynx 4.1 software with TargetLynx.

For real sample analysis, urine samples collected from healthy population with no known exposure to pyrethroids and from farm workers actively using pesticides in daily practice (provided by Dr. S. Hongsibsong from Chiang Mai University) were completely hydrolyzed with concentrated hydrochloric acid according to a previous study.[24] The hydrolyzed products by appropriate pH value adjust-

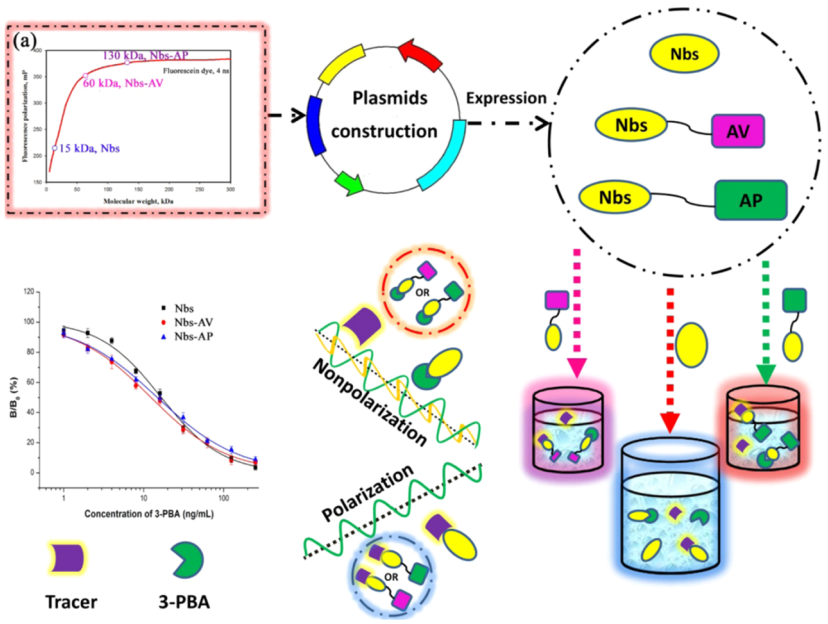

Figure 3. Schematic illustration of the different-sized Nbs for 3-PBA FPIA. In a homogeneous FPIA, the analyte 3-PBA and fluorescent tracer antigen conjugates competed for the binding sites of the anti-3-PBA Nbs. As a result of competition, the polarization signal was inversely proportional to the concentration of 3-PBA. Construction of specific-sized Nbs was guided by the relationship curve between polarization and molecular weight for the fluorescein tracer to cover distinct regions of the curve; inset figure (a) was adapted with permission from ref 18. Copyright SAGE Publications, 2000.

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ment (pH at 8.0 for FPIA and 6.0 for LC−MS) were used in the Nb-based FPIA and LC−MS.

3. RESULTS AND DISCUSSION

3.1. Characterization of the Tracer Antigen Conjugate. The design of the tracer antigen conjugate is a critical step in FPIA development. A fluorescein analog 4′-(aminomethyl)fluorescein (4-AMF) with a fluorescence lifetime of 4 ns was specifically selected as the fluorescence reporter due to a relatively sharp fluorescence polarization−molecular weight correlation curve and availability of these group of dyes.[18] A hapten for 3-PBA with a handle attached to the 4-position of the distal phenyl group has been shown to give highly sensitive immunoassays according to our previous report.[22] The 3-PBA hapten conjugated to 4-AMF fluorescein to form a Schiff base complex was first characterized and purified by TLC, which had a distinctive yellow band with a retention factor (R_f) of 0.55 (Figure S1A). The MS/MS spectral results showed an expected peak at m/z ([M + 1]+) 618.3 (data not shown). From the fluorescence polarization (FP) test, the tracer conjugate showed obvious binding to the specific polyclonal antibody against 3-PBA (Figure S1B), indicating the successful synthesis of the tracer conjugate.

3.2. Identification of Nbs. The polarization−molecular weight relationship curve for the fluorescein tracer shows a sharp increase of the polarization value as the molecular weight increases from 0 to nearly 30 kDa, nearly saturation at the molecular weight range of 30−100 kDa, and complete saturation above 100 kDa (Figure 3a).[18] Thus, to investigate the effect of antibody size on the sensitivity of FPIA, we picked one point in each range as follows: 15, 60, and 130 kDa, respectively. Rhizavidin and alkaline phosphatase were selected as fusion partners for recombinant expression of Nbs-Avidin (Nbs-AV, 60 kDa) and Nbs-alkaline phosphatase (Nbs-AP, 130 kDa) dimer fusion proteins based on genetic fusion protein technology. Both rhizavidin and alkaline phosphatase have been proven to be good fusion partners for recombinant antibody production with good yield and stability.[25,26] In addition, Nbs have been widely utilized in recombinant antibodies as alternatives to traditional single chain antibodies (scFv) due to their excellent solubility and ability to refold after denaturation.[27,28]

Genetic fusions allow one to finely tune the molecular weight of the resulting fusion protein, while retaining the recognition ability against the analyte. Meanwhile, genetic fusions prevent the need to prepare chemical conjugates, which sometimes show disadvantages in terms of high heterogeneity and reduced antibody activity.[25] The constructed recombinant plasmids of Nb were confirmed by PCR and DNA sequencing, respectively. Positive recombinant plasmids were transformed into *E. coli* BL21 (DE3) cells for protein expression, and the resulting Nbs were purified using a Ni-NTA affinity column. The size and purity of the proteins were verified on NuPAGE 12% Bis−Tris Protein gel (Thermo Fisher), where the purified Nbs and Nbs-AV and Nbs-AP fusion proteins showed the expected bands of approximately 15, 30, and 65 kDa, respectively (Figure 2). The binding characteristics of the original Nb were preserved in the fusion proteins as shown in the competitive enzyme-linked immunosorbent assay (ELISA) experiments (data not shown).

3.3. Analytical Characterization. Under the optimized conditions (optimized concentrations of tracer and antibodies, Supporting Information), the half-maximal inhibitory concentration (IC_{50}) levels obtained by the competitive FPIA based on sigmoidal inhibition curves were 16.4, 12.2, and 14.8 ng mL^{-1} for Nbs, Nbs-AV, and Nbs-AP, respectively (Figure 4). It

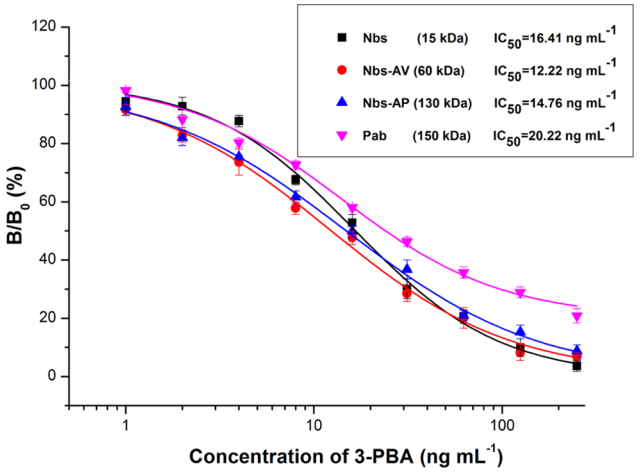

Figure 4. Standard inhibition curve for different-sized antibodies (Nbs, Nbs-AV, Nbs-AP, and Pab) in FPIA for 3-PBA.

appears that similar IC_{50} values are indicative of the negligible effect of Nb size on the sensitivity (at MW > 15 kDa) (here "sensitivity" is straightforwardly expressed as IC_{50}) of a competitive FPIA.

In a typical competitive immunoassay system, the sensitivity has been empirically proven to be associated with the concentration and affinity/avidity of antibody and antigen (even subdivided to associate with the valence and the heterogeneity of antibody and/or competitive antigen) as well as the properties of signal tags.[19,20,29,30] In our FPIA system, we used one kind of monovalent tracer (1:1 molar ratio of 3-PBA hapten and 4-AMF fluorescein), thus eliminating the variability associated with the change of the antigen structure, the valence of the antigen, and the quantum yield of signal tags. The Nbs and the two Nb fusion proteins had very similar affinity constants (K_d = 17 nM for bare Nbs, K_d = 12 nM for Nbs-AV, and K_d = 15 nM for Nbs-AP, Supporting Information), which is not surprising based on the fact that all three proteins have the same protein sequence of the binding domain. The affinities of Nbs-AV and Nbs-AP were slightly higher than that of bare Nbs, which was probably due to the dimer nature of those fusions (avidity contribution). The increased affinity of the two fusion Nbs is attributed to the increase in sensitivity resulting from the formation of a divalent complex. This further indicates the negligible effect of the Nb size (at MW > 15 kDa) on the sensitivity of the competitive FPIA.

In addition, the sensitivity (IC_{50}) of the traditional polyclonal antibody (Pab)-based FPIA was 20.2 ng mL^{-1} (Figure 4), which compared well with the Nb-based FPIA. This result was consistent with the trend result we previously reported for corresponding ELISAs (ELISA IC_{50} (Pab) = 1.65 ng mL^{-1}; IC_{50} (Nb) = 1.4 ng mL^{-1}).[21,22] The empirical observation that FPIAs have one order of magnitude lower sensitivity than classical ELISAs[16,31] seems to hold for the assay developed here as well.

In summary, the Nb size has no significant effect on the sensitivity of a competitive FPIA at least for fluorescein-based reporters but probably more generally for reporters with

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Table 1. Comparison of Performance of Nb-FPIA and LC−MS for Quantification of 3-PBA in Urine (n = 5)

	Nb-FPIA			LC−MS		
spiked concentration (ng mL^{-1})	found ± SD[a] (ng mL^{-1})	recovery (%)	CV[b] (%)	found ± SD (ng mL^{-1})	recovery (%)	CV (%)
100	89 ± 6	89	6.7	84 ± 8	84	9.5
400	356 ± 15	89	4.2	368 ± 7	92	1.9

[a]Mean measured concentration of five replicates ± standard deviation. [b]Coefficient of variation of five measurements.

lifetimes ≤4 ns. Additionally, the Nb-based FPIA shows comparable sensitivity to the traditional Pab-based FPIA. All of these indicate that Nbs absolutely meet the sensitivity requirement of the FPIA that a traditional antibody achieves and are expected to boost the development of Nb-based FPIAs.

3.4. Nb-Based FPIA on Urine Samples. A common urinary metabolite of pyrethroids in mammals is 3-PBA, which was shown to be a biomarker of human exposure to pyrethroids.[22] In the present study, urine was selected to evaluate the performance of the Nb-based FPIA as well as the recovery of 3-PBA from spiked urine samples. Different concentrations of 3-PBA at 100 and 400 ng mL^{-1} were spiked into urine from healthy volunteers, respectively. To reduce the matrix effect of urine samples, the spiked sample solutions were diluted 20-fold prior to the analysis for FPIA (Figure S3). Table 1 shows the average recovery values (n = 5) of 89% with coefficients of variation (CVs) below 6.7%. The recovery results of the spiked samples obtained by the Nb-based FPIA are in good agreement with those obtained by LC−MS, confirming the reliability and practicability of this Nb-FPIA for 3-PBA analysis. As shown in Table S1, positive real urine samples containing concentrations of 3-PBA higher than 50.6 ng mL^{-1} are accurately detected by the developed Nb-FPIA. To detect lower concentrations of 3-PBA, sample preparation by solid-phase extraction (SPE) or a mixed-mode SPE method should be recommended for use.[23]

In this study, we investigated the effect of nanobody (Nb) size on the sensitivity of fluorescence polarization immunoassay (FPIA). Three different molecular weight Nbs against 3-phenoxybenzoic acid (3-PBA) were specifically generated to cover distinct regions on the polarization−molecular weight relationship curve for the fluorescein tracer. Similar half-maximal inhibitory concentration (IC_{50}) levels of the three different molecular weight Nbs indicated that the size of Nbs had no significant effect on the sensitivity of the competitive FPIA. Comparable sensitivities between Pab- and Nb-based FPIAs further pointed at the value of Nb as an alternative for the development of the FPIA. Application of Nb-based FPIA to the analysis of spiked urine and real urine samples showed excellent recoveries of the 3-PBA analyte and good correlation with LC−MS results. It appears that the scarcity of reports on the application of Nbs in FPIA is not related to their relatively small molecular weight (and thus poor sensitivity) but rather to other reasons like limited availability of Nbs, particularly to small molecular compounds which proved to be hard targets due to the high failure rate of Nb generation and failure to compete with the small molecule reporter of the Nb. We hope that our research will not only boost the development of Nb-based FPIAs but also lead to significant improvements in this field by taking advantage of the outstanding properties of Nbs, which make them stand out as unique analytical tools.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.jafc.9b04621.

Construction of recombinant plasmid; expression and purification of Nbs; optimization of tracer and Nb dilutions; affinity measurement; matrix effect in urine samples; primers utilized in this study; quantification of 3-PBA in the urine samples of persons exposed to pyrethroids (PDF)

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Notes

The authors declare no competing financial interest.

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