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Reversible Immuno-Infrared-Sensor for the Detection of Alzheimer´s Disease Related Biomarkers

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ABSTRACT: The development of biosensors for medical purposes is a growing field. An immuno-infrared-biosensor for the preclinical detection of Alzheimer's disease (AD) in body fluids was developed. The key element of this sensor is an ATR-crystals with chemical modified surface to catch the biomarker out of the body fluid. So far, the immuno-infrared sensor can be used only once and require time-consuming steps of sensor exchange, sensor cleaning and novel surface functionalization. Here, we developed an immuno-infrared-sensor providing a reusable surface and showcase its performance by the detection of the AD biomarker proteins Aβ and Tau in human CSF. The sensor surface is covalently coated with the immunoglobulin binding proteins Protein A or Protein G. These were employed for non-covalent immobilization of antibodies and the subsequent immobilization and analysis of their antigens. The reversible antibody immobilization can be repeated several times with the same or different antibodies. Further, the more specific binding of the antibody via its Fc region instead of the conventional NHS coupling leads to a 3-4-fold higher antigen binding capacity of the antibody. Thus, the throughput, sensitivity and automation capacity of the immuno-infrared-biosensor are significantly increased as compared to former immuno-infrared-assays. This immuno-sensor can be used with any antibody that binds to Protein A or Protein G.

Alzheimer's disease (AD) is the most common neurodegenerative disease. Early diagnosis of AD is a key factor for future therapies. Today, disease related biomarkers such as Amyloid-β (Aβ) and Tau are measured in CSF and recently in blood[1-4]. Already in 2016, an immuno-infrared-sensor was applied to detect the Aβ secondary structure distribution in CSF and blood plasma of moderate to severe AD cases and disease control subjects.[1,2] In 2018 the sensor was validated also for the identification of preclinical AD stages in average 8 years before clinical manifestation with a sensitivity of 71% and specificity of 91%.[3] Most recently, combination of plasma and CSF Aβ and Tau analyses yielded in a sensitivity of 87% and specificity of 97%.[4] This sensor is based on an antibody functionalized surface where antibodies are covalently attached. An easy regeneration of the biosensor surface will significantly enhance its applicability. Surfaces often have to be immersed into harsh chemicals, are polished or even discarded. Thus, reusing the sensor surface is limited.

In most immuno-assays, such as ELISA, antibodies are unspecifically adsorbed or covalently bound to surfaces with random orientation[1,5,6] which can influence the efficiency of antigen binding.[7] Immunoglobulin binding proteins show promising properties towards specific and reversible binding of antibodies.[8–11] A non-covalent immobilization of specific IgG antibodies via Protein A and G leads to a distinct orientated antibody layer on the surface. Protein A and G mediate a high affinity interaction with the Fc constant region of the IgG antibody, which is reversible using chemical treatment, e.g. pH change.[12]

Here, we introduce Protein A and G as capturing agent on ATR-Germanium crystals. This new assay provides a reversible platform for rapid and robust analyses of human blood and CSF samples for AD diagnosis.

EXPERIMENTAL SECTION

Surface modification of Germanium

The surface modification of ATR-germanium crystals via silane chemistry was described previously.[1,3,13] Briefly, the germanium crystals were incubated for 10 min in 90% H_2O_2/10% oxalic acid. Afterwards, ATR-crystals were incubated with 300 µM NHS-Silane solution for 60 minutes followed by subsequent removing of unbound compounds with 2-propanol. In a next step, the sensor was buffered in HEPES buffer (50 mM HEPES; pH 7.4). Subsequently, 100 µg of Protein A or G was added on the NHS-Silane functionalized sensor surface for 1 h. Unbound proteins were removed by rinsing the sensor with HEPES buffer. Before binding of different antibodies the sensor surface was saturated with a casein blocking solution for 15 min to disable reactive sides. Finally, the antibody was captured by the Protein A or G[8] -modified surface by exposure to a 66 nM solution of antibody for 30 min.. Unbound antibody particles were rinsed off for at least 30 min with HEPES buffer. According to the antibody subtype, monoclonal antibody A8978, and Tau-5 were applied to Protein A functionalized sensor surfaces, whereas the monoclonal antibody HJ5.1 was attached to a protein G functionalized sensor surface. For each preparative step infrared-difference spectra were recorded. A detailed description can also be found in former publications.[1–3]

Measurement of synthetic Aβ and recombinant Tau

Synthetic Aβ(1-42) fibrils were prepared as described in Nabers, Ollesch et al.. Recombinant Tau was expressed at the Department of Biophysics (Bochum, Germany). Briefly the gene coding for

full length Tau was transformed in BL21 DE3 cells. For plasmid selection the cells were incubated on LB-agar plates containing 100 µg/ml Kanamycin and 0.2% glucose at 37 °C overnight. A preculture (LB-medium, 100 µg/ml Kanamycin, 0.2% glucose) was inoculated and incubated at 37°C and 140 rpm overnight. For mainculture 4 l LB were inoculated with the preculture and shaked in 1l flasks. At an OD_{595} of 0.6 protein expression was induced using 1 mM 1-thio-^{L}-D-galactopyranoside for 3,5 hours. The cell pellet was resuspended in MES-KOH (50 mM MES, 500 mM NaCl, 1mM $MgCl_2$, 5 mM DTT, pH 6.9) and boiled for 20 minutes at 100 °C. The homogenate was then centrifuged at 100000 x g and 4 °C for 45 minutes. Finally, the supernatant was concentrated with a 30 kDa centrifugal filter.

However, 20 µg Aβ fibrils or 100 µg Tau were added to the antibody functionalized sensor surface in a circulating flow for 45 minutes. Unbound proteins were rinsed for 30 minutes with HEPES. For the measurements of synthetic Aβ peptides the antibody A8978 (Sigma Aldrich, Germany), whereas Tau-5 (Thermofisher) was used as capture antibody for recombinant Tau.

Measurement of CSF samples

Before any measurement CSF samples were preincubated with 500 µg Pierce™ Protein G Magnetic Beads, 500 µg Pierce™ Protein A Magnetic Beads and 500 µg Pierce™ Protein A/G Magnetic Beads for 3 hours at 7°C in order to avoid binding of human IgGs from the sample to surface immobilized Protein A or G. For the immuno-infrared-analysis 100 µl of CSF samples were circulated over the surface for 45 min in order to extract the Aβ peptide or Tau protein fraction from the body fluid. Remaining proteins of the CSF samples were rinsed for 30 min with HEPES buffer. Thus, only the Aβ or Tau secondary structure distribution in human CSF samples was detected. For the detection of Aβ from body fluids monoclonal antibody HJ5.1 (Holtzman, Washington, USA) was used instead of A8978 because of the higher affinity to various Aβ conformational isoforms.

Regeneration of the sensor surface

For repeated measurements the extracted Aβ or Tau fraction, as well as the antibody layer, were eluted from the sensor surface with 100 mM Glycine (pH 2) for 10 min. The equilibration with HEPES buffer was finished after 10min. Afterwards, the protein A or G functionalized sensor surface was refreshed and could be used for a further antibody-binding process inclusive Aβ or Tau extraction from liquid solutions as described above.

Fluorescence Analysis

Before fluorescence analysis, the sensor surface was covalently functionalized with Protein A and rinsed with HEPES buffer as described above. Afterwards, 5 µg FITC-labelled monoclonal antibody 9F1 (Nanotools, Antikörpertechnik GmbH, Tenningen, Germany) was incubated for 30 min and unbound antibodies were rinsed off with HEPES buffer.

Fluorescence measurements were performed using the set-up and protocols as previously published in Nabers, Ollesch et al. 2016.[1]

In summary, Fluorescence signals were obtained through the quartz glass window (40 x 10 mm) of the ATR-flow-through-cell using a 100 times magnification and 2 s exposure time. The FITC-labeled antibody was excited with 484 nm and emission was recorded at 518 nm. The contrast was enhanced by a factor of 3. As readout we calculated the mean brightness value of all pixel of the green channel.

Subsequently, we inserted again the flow-cell in the spectrometer for further FTIR-measurements.

Finally, the antibody bound to Protein A was eluted from the sensor surface with glycine pH 2 for 10 min and fluorescence intensity was recorded as described above.

RESULTS AND DISCUSSION

The usage of Protein A and Protein G as non-covalent antibody capturing agents provides a reversible sensor surface for the repeated immobilization of different IgG antibodies in the immuno-infrared-assay. First, a self-assembled monolayer of NHS-silanes was generated with subsequent covalent immobilization of immunoglobulin binding proteins such as Protein A or Protein G (Figure 1, step zero; Figure S1, S2). The corresponding infrared spectra of Protein A and G, especially the amide I and II bands, are presented in Figure S3 and Figure S4, respectively. In the next step, unreacted esters or free bindings sites on the sensor surface were blocked with casein (Figure 1, step one).[1] Subsequently, different antibodies were added to the system (Figure 1, step two). The non-covalent immobilization of monoclonal antibody A8978 for Aβ detection reached an absorbance plateau after 30 min. After rinsing for 15 min with HEPES buffer sufficient amounts of immobilized antibodies remained on the sensor surface (Figure 2A). Now the sensor is ready for biomarker detection (Figure 1, step three). In general, antibody immobilization by Protein A or G was performed for 1 h with subsequent 30 min rinsing with HEPES to reveal an antibody absorbance plateau after washing (Figure S5). Only for the better illustration of repeated antibody immobilization cycles in Figure 2 we reduced incubation and rinsing time.

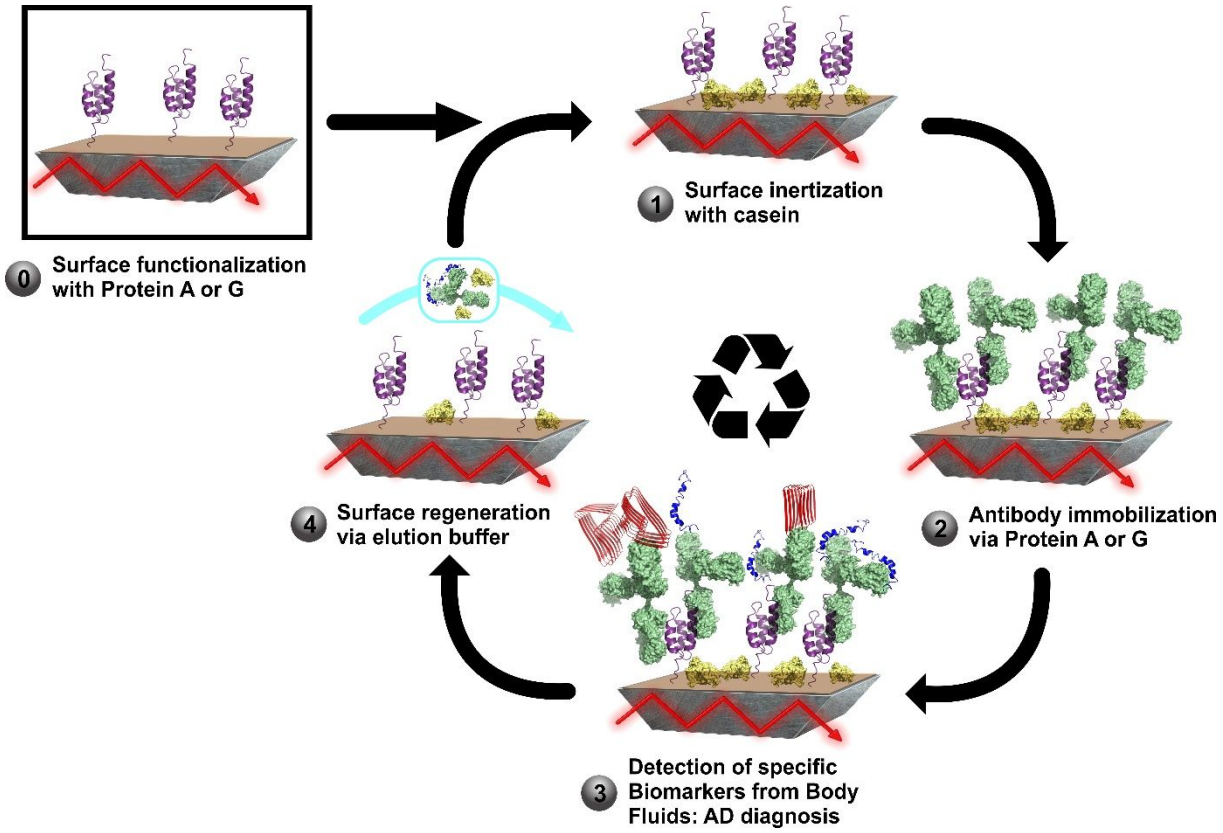

Figure 1. General principle of the reversible immuno-infrared-assay. First, immunoglobulin binding proteins such as Protein A or G are covalently coupled to the sensor surface via silane chemistry (step zero). Free reactive sites on the surface are saturated with blocking solution (step one) before antibody immobilization (step two). The functionalized sensor can be used, for example, for the detection of AD biomarkers in aqueous solution or body fluids for AD diagnosis (step three). Finally, antigen-antibody complexes can be removed with elution buffer (step 4) and the sensor can be reused by starting with step 1.

The sensor surface can be reused after antibody elution by washing the surface with glycine (pH 2) for 10 min (Figure 1, step 4, Figure 2A). The following washing step with HEPES buffer revealed that the antibody layer was completely removed (Figure 2A). The negative absorbance is caused by a loss of blocking agent as can be assigned by its spectral signature (Figure S6). Therefore, after elution, each cycle started with another saturation of free reactive sites on the sensor surface by casein. A full set of both, raw data and processed data indicating the sensor functionalization is given in Figure S7. The reusability was investigated for seven cycles over two days. The amount of immobilized antibody decreased from a maximum of 7.2 mOD on cycle 2 to 6.1 mOD on cycle 7 (Figure 2A). However, even 35 cycles performed over 7 days were possible (Figure S8). The binding properties among the cycles do not change significantly as shown by the highly reproducible absorption spectra obtained after the extraction of synthetic fibrillar Aβ(1-42) by the monoclonal antibody A8978 (Figure 2B). Further evidence is the similarity of the Protein A spectrum before and after glycine treatment (Figure S9), and the similarity of the antibody spectra among the seven binding cycles (Figure S10). Thus, the sensor surface can be easily regenerated and used for repeated analyses in at least seven cycles without significant loss in performance. There is no need of dismantling the sensor from the spectrometer, subsequent polishing, renewed surface activation, and surface functionalization. This saves measurement time, reduces user input, and automatization of the system is much easier.

For further validation of the elution of antibodies from the Protein A or G terminated surface, fluorescence analyses was performed: FITC-labeled monoclonal antibody 9F1 (mAb^{FITC}) was attached to a Protein A terminated sensor surface in an identical manner as described above but directly under a fluorescence microscope. Fluorescence intensity was recorded during the binding and rinsing process, and after elution of the FITC-labeled antibody fraction. After the fluorescence intensity was stable in the washing step, the antibody was eluted using 100 mM Glycine pH 2 for 10 minutes.

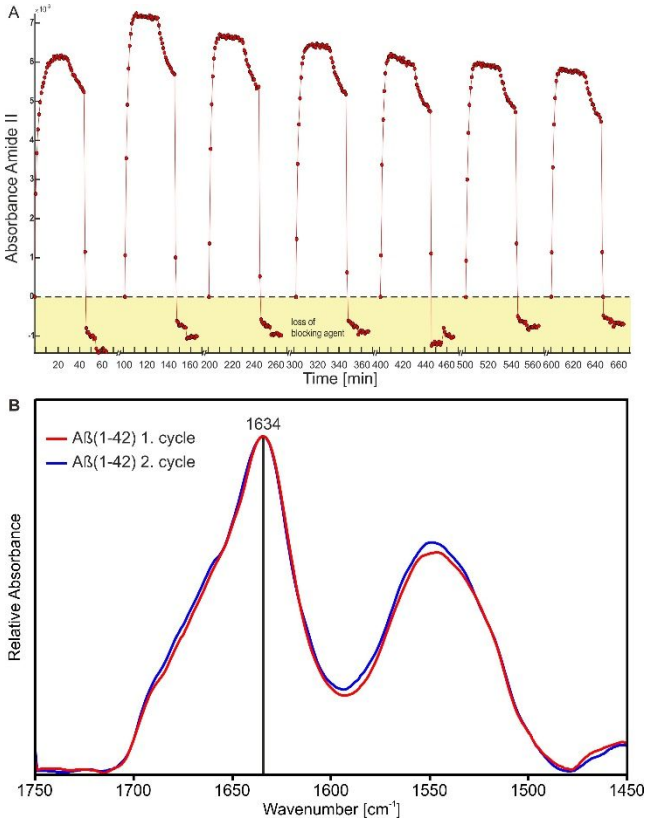

Figure 2. Repeated immobilization of antibody and reproducible binding of antigen. (A) Repetitive binding of antibody A8978 on the reversible immuno-infrared-sensor surface. After binding of antibody at Protein A (30 min) and subsequent rinsing with HEPES buffer (15 min), the surface would be ready for antigen analysis. Here we eluted the antibody via glycine pH 2 (10 min) followed by rinsing with buffer (10 min). This procedure was repeated 7 times. After each cycle, the surface was saturated with casein because of loss of blocking agent after antibody elution (see also Figure S5). (B) Synthetic Aβ(1-42) was detected repeatedly with monoclonal antibody A8978 on Protein A. The resulting absorbance spectra of Aβ were highly comparable with an identical amide I frequency at 1634 cm^{-1}.

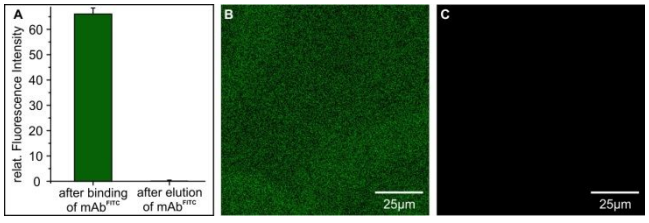

Figure 3. Validation of antibody immobilization and elution on the reversible immuno-infrared-sensor by the fluorescence intensity of a FITC-labelled antibody 9F1 (mAb^{FITC}). (A,B) The green fluorescence was recorded after mAb^{FITC} attachment on Protein A and subsequent rinsing with buffer (B). (A,C) After mAb^{FITC} elution with glycine pH 2 and buffer rinsing no fluorescence intensity was observed (C) confirming the reversible character of the sensor surface.

As shown in Figure 3, the relative green fluorescence intensity was 65.0 after immobilization of mAb^{FITC}. In contrast, after elution of the antibody fraction the relative green fluorescence intensity was 0.0. These results confirmed the spectral results of the elution process highlighted in Figure 2A.

Most antibody immobilizations are done by unspecific adsorption or by covalent coupling of amine residues of the antibody to surface bound NHS-groups.[2,13] This leads to a random orientation of the antibody and only a fraction will be able to bind the antigen. Especially surface binding via the N-termini of the antibody is disadvantageous, because they are close to the antigen binding site. In contrast, the immunoglobulin binding proteins used in our approach bind the antibody at the Fc region, leaving the Fab region unperturbed. This leads to a 3-4-fold increase of antigen binding per immobilized antibody as shown in Figure S11. Note that the antibody spectra were very similar in both cases, suggesting a native antibody surface (Figure S12).

In a next step, we wanted to validate the reproducibility of the reversible surface for the analysis of the Aβ secondary structure distribution in CSF. Therefore, pooled CSF samples of AD patients and health control (HC) subjects were measured separately (Figure 4). The recorded Aβ IR-difference spectrum represents an integrated signal over all conformational Aβ isoforms present in the respective body fluid. This secondary structure distribution of all Aβ isoforms can be used in an immuno-infrared-assay for the diagnosis of Alzheimer´s disease (Figure 1, step 3).[2] In a former study, AD patients demonstrated a higher content of β-sheet enriched isoforms in the total Aβ fraction, resulting in a lower amide I maximum position as compared to disease control subjects. Thus, AD was detected by a simple threshold classifier with maxima below 1642 cm^{-1} indicative for AD. Indeed, in the case of an AD sample the maximum of the amide I band of Aβ was 1638 cm^{-1}, below the threshold. On the other hand, in the case of an HC CSF sample the corresponding maximum was1643 cm^{-1}, above the threshold. We compared these results with data of the same patient samples obtained with the former non-reversible immuno-infrared-assay. As shown in Figure 4 the amide I bands of Aβ were highly comparable between both assays and most importantly the maxima of the amide I bands are identical, leading to the same diagnoses. Identical maxima were also obtained in measurements with synthetic Aβ (Figure S13).

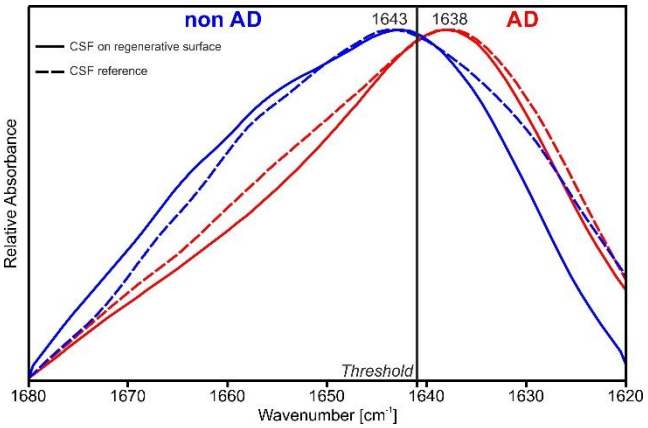

Figure 4. Reproducibility of the reversible sensor surface with Aβ from CSF in comparison with former results on a non-reversible surface as a control. Aβ from CSF as measured with antibody HJ5.1 on Protein G (solid lines) revealed results highly comparable to the literature (dashed lines).[2] For AD cases (in both cases maximum below the discriminative threshold) and HC subjects (both above the discriminative threshold) maxima were identical, indicating that the reversible immuno-infrared-sensor can be used for AD diagnostics.

We could demonstrate that the reversible surface allows the extraction of Aβ from CSF and thus the diagnosis of AD using a simple threshold classifier. The obtained results were in high agreement with former results received with the covalently linked antibody surface.[1,3] To further validate the regenerative sensor, we performed multiple Aβ extractions from pooled CSF. It was possible to extract Aβ from pooled CSF in successive cycles and between independent experiments with no loss in performance (Figure S14, S15). The average maximum of the detected amide I band of extracted Aβ was 1637.4 cm^{-1} +/- 0.6 over 5 measurements (Figure S16). Thus, the regenerative sensor demonstrated lowest inter-measurement variabilities and can be used for screening in clinical studies.

Note that, as described in the method section, the complete removal of any IgG fractions within a sample is necessary for the reversible sensor, because IgG's could bind to free binding sites of the immobilized immunoglobulin binding proteins (Figure S17). Consequently, the recorded amide I band after Aβ extraction would have strong spectral contributions from human IgG antibodies. This would lead to an absorbance downshift due to IgG's high content of β-sheet structures, interfering with diagnostics.

AD pathology is characterized by abnormal misfolding or altered concentration of different biomarkers, e.g. Aβ, Tau, Neurofilament light chain (NFL), neurogranin, or YKL-40.[14–16] Levels of these biomarkers were determined in CSF and used as gold standard for AD neurochemical diagnostics. Appropriately, a reversible sensor could subsequently detect multiple biomarkers. Since the Tau protein is also known to undergo a structural change from monomeric to aggregated β-sheet enriched species, we used the reversible immuno-infrared-sensor to detect both Aβ and Tau, respectively. In a first step, monoclonal antibody Tau-5 was attached to the surface linked Protein A layer.

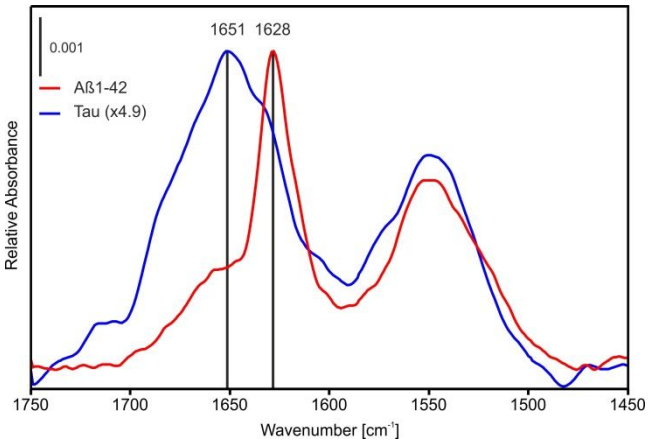

Figure 5. Detection of different AD biomarkers using the reversible immuno-infrared-sensor. In a first step, antibody Tau-5 was immobilized on the Protein A coated sensor surface in order to capture recombinant Tau from aqueous solution. After elution of the antibody-antigen complexes, antibody A8978 was immobilized on the same sensor surface to capture fibrillar Aβ(1–42) from aqueous solution. Between both steps, the sensor surface was saturated with casein for surface inertization (Figure 1).

Therewith, recombinant Tau was extracted from a liquid solution in a monomeric state. After elution of Tau-5/Tau protein complexes from the surface, monoclonal antibody A8978 was attached to the Protein A layer to extract fibrillar Aβ from an aqueous solution. We used monomeric Tau and fibrillar Aβ as the two extreme protein conformations involved in AD pathology. Both conformations showed highly significant differences in the amide I region (Figure 5) which clearly demonstrated that the reversible immuno-infrared-sensor can be used to successively detect different AD biomarkers and determine their secondary structure for diagnostic purposes.

CONCLUSION

By employing immunoglobulin binding proteins such as Protein A and G as antibody capturing agents in an immuno-infrared assay makes the workflow convenient, easy to handle, more cost, material, and time efficient and significantly increases the throughput of the method. Thus, this assay can be used as biomarker screening tool e.g. in clinical studies for early AD detection as demonstrated before.[3]

In contrast to assays where the capture antibodies are covalently linked to the sensor surface, the reversible set-up has an approximately factor 6 increased throughput with a highly comparable performance. The signal/noise is significantly improved due to the more specific immobilization of the antibody via the Fc region. Additionally, the reversible assay is completely automatized and can be applied 24 h 7 days a week.

ASSOCIATED CONTENT

Supporting Information

Figure S1: Binding kinetics of Protein A S2: Binding kinetics of Protein G S3: Difference spectrum of immobilized Protein A S4: Difference spectrum of immobilized Protein G S5: Long-term binding kinetics of antibody A8978 S6: Spectral comparison of antibody elution and casein S7: Compilation of infrared spectra recorded during the sensor functionalization, elution, and recovery of an antibody functionalized reversible immuno-infrared-sensor surface S8: Influence of elution buffer on protein A S9: Comparison of antibody spectra during repeated immobilization S10: Comparison of the binding capacities for the current sensor and the regenerative sensor S11: Comparison of antibody spectra immobilized on NHS-silane and protein A S12: Comparison of antibody spectra immobilized on NHS-silane and protein A S13: Immobilized Aβ on current system and regenerative surface S14: Comparison of the detection of Aβ from pooled CSF in the first cycle of antibody binding and elution and the last cycle S15: Comparison of the detection of Aβ from pooled CSF in different cycles of antibody binding and elution S116: Mean spectrum and standard deviation of pooled AD CSF samples. S17: Spectral quality control of IgG depletion from CSF

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Author Contributions

The manuscript was written through contributions of all authors. / All authors have given approval to the final version of the manuscript.

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ABBREVIATIONS

AD, Alzheimer´s Disease; HC, health control; Aβ, Amyloid-β; ATR, attenuated total reflection; CSF, cerebrospinal fluid; IgG, Immunoglobulin; mOD, milli optical density; HEPES, 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid; FITC, Fluorescein isothiocyanate; mAb, monoclonal antibody; NHS-silane, N-hydroxy succinimidyl-ester triethoxysilane; NFL, Neurofilament light chain

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