A direct enzyme-linked immunosorbent assay (ELISA) for the quantitative evaluation of Janus Kinase 3 (JAK3) inhibitors

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The availability of a robust, precise and cost-efficient test system is the prerequisite for the performance of any medicinal chemistry program, especially in an academic environment. For the identification of novel Janus Kinase 3 inhibitors and determination of structure–activity relationships, a direct enzyme-linked immunosorbent assay was developed. Being applicable in a standard laboratory, the main advantage over existing methods is the basic equipment requirement as this assay does not need special handling originating from the use of cell cultures or radiometric readout. In contrast to earlier methods relying on two-step procedures, our assay uses a single peroxidase conjugated antibody to quantify and detect substrate phosphorylation. This optimized assay features a limit of detection of 0.032 μg mL⁻¹, a wide dynamic range of 0.638 OD units and an appropriate Z′ factor of 0.66. The determined IC₅₀ value for Tofacitinib was 3.5 ± 0.6 nM (n = 18). A detailed assay protocol custom-tailored for the JAK3 kinase domain and a step-by-step manual for optimizing specific assay conditions are presented. This ELISA primarily addresses researchers within the academic setting facing the task to identify lead structures and explore structure–activity relationships of JAK3 inhibitors at reasonable costs.

Introduction

Janus kinases (JAKs) are a group of non-receptor tyrosine kinases playing a fundamental role in the immune system, hematopoiesis and interferon signaling. Consequently, the four JAK family members JAK 1,2,3 and Tyrosine Kinase 2 are highly attractive targets for treatment of inflammatory and oncological disorders.1–3

Several inhibitors of JAK1 and/or JAK2 as well as pan-JAK inhibitors are currently under clinical investigation for treatment of inflammatory disorders like rheumatoid arthritis (RA) and autoimmune diseases such as Crohn’s disease and psoriasis. Recently, the pan-JAK inhibitor Tofacitinib has been approved by the US Food and Drug Administration (FDA) for its application in patients with severe RA inadequately responding to methotrexate.4 However, the European Medicines Agency (EMA) refused the marketing authorization of Tofacitinib in 2013 due to an increased risk for the occurrence of serious infections among other severe side effects.5

In contrast to the other JAK family members, the expression of JAK3 is restricted to the hematopoietic tissue where it exclusively associates with cytokine receptors bearing the common gamma-chain (γc) subunit, enabling JAK3 to specifically operate in immune cells. Consequently, JAK3 represents an attractive target for immunosuppression with limited side effects. Nevertheless, no selective JAK3 inhibitor is available for therapy so far and there is a lack of sufficiently characterized compounds with a distinct selectivity profile. Despite its poor selectivity within the JAK family Knapp et al. suggested the pan-JAK inhibitor Tofacitinib as a high-quality chemical probe for JAK3.6 To evaluate the JAK3 activity of our Tofacitinib-derived compound library,7 we modified, adapted and optimized a general enzyme-linked immunosorbent assay (ELISA) for the detection of protein tyrosine kinase activity previously established by Lázaro et al.8 Earlier published non-cellular JAK3 assays were based on radiometric formats or depended on multi-step procedures using expensive reagents. In contrast, our protocol is operationally simple, robust, and performable at a low cost making it a useful tool for routine screening of JAK3 inhibitors, especially in an academic environment. The ELISA reported herein allows the determination of inhibitory potencies in the low nanomolar range and the IC₅₀ values obtained were subsequently confirmed by commercial radiometric and cellular assays. As a result of our research in this area, we recently described a new class of highly potent tricyclic JAK inhibitors with superior selectivity compared to Tofacitinib.9

In the general assay procedure reported by Lázaro et al., an artificial synthetic polypeptide consisting of L-glutamic acid and L-tyrosine in random distribution with a molar ratio of 4 : 1 of glutamic acid to tyrosine is adsorbed to the wells of the assay
plate. In the presence of tyrosine kinase and ATP, the synthetic
polypeptide is phosphorylated on its tyrosine residues while
ADP is generated. The amount of the phosphorylated kinase
substrate directly correlates with kinase activity. The compari-
sion of the maximum phosphorylation level with the phos-
phorylation degree achieved when the JAK3 kinase reaction is
carried out in the presence of different inhibitor concentra-
tions allows the determination of IC₅₀ values.

For detection, Lázaro’s protocol applies a two-step proce-
dure. As a primary antibody, a monoclonal mouse anti-phos-
phorysine antibody is used while a goat anti-mouse
immunoglobulin G (IgG) antibody labeled with peroxidase
serves as a secondary antibody. This method requires two
incubation steps, one for each antibody reaction. In contrast,
our novel protocol uses a single monoclonal anti-phosphorysine
antibody conjugated with peroxidase for directly detecting
the degree of phosphorylation of the synthetic polypeptide, as
illustrated in Fig. 1.

Experimental

Materials and methods

Reagents and labware. All reagents were of ultra-pure grade
except as noted otherwise. If not described differently, all
pipetting was carried out using Eppendorf Reference® pipets in
combination with the respective size of Eppendorf epT.1.P.S.
Standard®. The monoclonal anti-phosphorysine–peroxidase
coupled antibody (Catalog # A5964), the synthetic poly-
peptide serving as the kinase substrate (Catalog # P0275), glob-
ulin free bovine serum albumin (BSA) (Catalog # A3059), DL-
dithiothreitol (Catalog # D9779), adenosine-5’-triphosphate
disodium salt hydrate (ATP) (Catalog # A2383) and sodium
orthovanadate (Na₃VO₄) (Catalog # S6508) were all obtained
from Sigma-Aldrich GmbH, Germany. The active JAK3 kinase
domain (amino acids 781 to 1124) was purchased from Abcam,
England (Catalog # ab89982). As additional ingredients of
the kinase buffer, 2-[4-(2-hydroxyethyl)piperazin-1-yl]ethane-
sulfonic acid (HEPES) (Catalog # L1613) was obtained from
Biochrom GmbH, Germany and MgCl₂ × 6H₂O (Catalog
#105833) was purchased from Merck KGA, Germany. Ultra-pure
water produced with an ELGA PURELAB Ultra Mk2 Genetic
water purification device was used throughout the work. The
3,3’,5,5’-tetramethylbenzidine (TMB) peroxidase reagent set
(Catalog # 555214) was obtained from B& l Biosciences Europe,
Nunc MaxiSorp® microtiter plates (flat bottom, 96 wells)
(Catalog # 442404) were purchased from Fisher Scientific
GmbH, Germany. Compound 1, 2 and the enantiopure refer-
cence Tofacitinib were prepared by modified literature pro-
ddures in our laboratory. Incubation was carried out in a
Heidolph Titramax 1000 shaking device combined with a Hei-
dolph Incubator 1000, Heidolph Instruments GmbH & Co. KG,
Germany. An Emax Precision-Microplate-Reader from Molec-
ular Devices GmbH, Ismaning, Germany equipped using
SOFTmax® PRO software from Molecular Devices GmbH,
Ismaning, Germany was used for readout.

Determination of the Z’ factor and dynamic range

The Z’ factor was calculated according to the general equation:

\[
Z' = 1 - \frac{3(\sigma_p + \sigma_n)}{\mu_p - \mu_n}
\]

The dynamic range is expressed by the term \(\frac{\mu_p - \mu_n}\).¹⁰

The variables of the equation refer to the following abbrevia-
tions: \(p\): OD₁₄₅₀ of positive control, \(n\): OD₁₄₅₀ of negative
control, \(\sigma\): standard deviation of OD₁₄₅₀, and \(\mu\): mean of OD₁₄₅₀.

Determination of the limit of detection (LOD)

A calibration curve of the phosphorylated polypeptide was
established and detection was carried out according to the
conditions described in the general assay procedure. The LOD
was assessed by linear regression of the calibration curve
applying the following equation:¹¹

\[
\text{LOD} = \frac{3\sigma}{S}
\]

The following abbreviations are used for the variables of the
equation: \(\sigma\): standard deviation of the response and \(S\): slope of
the calibration curve.

Calculation of the percentage of inhibition

The percentage of inhibition is calculated according to the fol-
lowing equation:

\[
\text{Inhibition}[^\%] = 100 - \left( \frac{\text{OD}_{1450}\text{Sample} - \text{OD}_{1450}\text{NSB}}{\text{OD}_{1450}\text{STIM} - \text{OD}_{1450}\text{NSB}} \right) \times 100
\]

\(\text{OD}_{1450}\text{STIM}\): the optical density at 450 nm for the positive
control (STIM); \(\text{OD}_{1450}\text{Sample}\): the optical density at 450 nm for
the kinase reaction in the presence of a test compound in the
respective dilution; \(\text{OD}_{1450}\text{NSB}\): the optical density at 450 nm for
nonspecific binding (NSB).
Adaption and optimization of the assay settings

To determine the optimal amount of the kinase substrate, a concentration row was prepared by dissolving the synthetic polypeptide in PBS. 100 µL of coating solution containing concentrations from 100 µg mL⁻¹ to 0.625 µg mL⁻¹ of the synthetic polypeptide were added to the wells of the assay plate. The plate was covered with a lid and coated overnight at 4 °C.

After the coating step, a kinase buffer (KB) with an ATP concentration of 100 µM was prepared. After one hour of incubation with pure KB and KB containing 60 ng mL⁻¹ JAK3 kinase and the subsequent antibody incubation step (dilution factor 1 : 60 000), optical densities (OD) of the nonspecific binding (NSB) signal and the maximum signal were detected at 450 nm (OD₁₅₀). For titration of the enzyme concentration, increasing amounts of JAK3 kinase (15 ng mL⁻¹ to 3840 ng mL⁻¹) were used while the ATP concentration of the KB was kept constant at 100 µM. The subsequent procedure was performed as described above for the determination of the kinase substrate concentration. For evaluating the dilution factor of the monoclonal peroxidase-labelled anti-phosphotyrosine antibody, the wells of the assay plate were coated with a 5 µg mL⁻¹ kinase substrate overnight at 4 °C. Pure KB with an ATP concentration of 1.4 µM was incubated as the negative control for the detection of the NSB signal. For determination of the positive control indicator the maximum signal, a KB containing 1.4 µM ATP and 60 ng mL⁻¹ of JAK3 kinase was employed. A dilution row with increasing amounts of the peroxidase-labelled anti-phosphotyrosine antibody was prepared in blocking buffer (BB: 0.1% Tween 20 and 0.25% bovine serum albumin in PBS) which had been adjusted to pH 6.5. 100 µL of the respective antibody dilution were added to the respective wells for both, positive and negative control, and incubated for one hour. The K_m value (Michaelis constant) for ATP was measured after coating the assay plate using 100 µg mL⁻¹ of the polypeptidic kinase substrate. The kinase reaction was carried out at a kinase concentration of 60 ng mL⁻¹ while varying the ATP concentrations from 0.1 µM to 1000 µM, maintaining the assay procedure as described above.

Results and discussion

General assay procedure

Prior to performing the assay, 10 mM stock solutions of samples and the reference compound Tofacitinib were prepared in dimethyl sulfoxide (DMSO). The polypeptidic kinase substrate was dissolved in PBS to obtain a final concentration of 5 µg mL⁻¹. 100 µL of this solution were added into all wells of the assay plate with an Eppendorf Multitette® plus equipped with a 5 mL Eppendorf Combitip plus®. The plate was closed with a lid and stored overnight at 4 °C for adsorption of the polypeptidic kinase substrate to its surface.

A KB containing 100 mM HEPES, 10 mM MgCl₂, 4 mM dithiothreitol, 0.1 mM Na₃VO₄, and 1.4 µM ATP was prepared in ultra-pure water and the pH was adjusted to 6.8–6.9 by dropwise addition of 1 M HCl. This KB solution served as a medium for both, preparation of the JAK3 enzyme solution and dilution of test compounds/reference. The enzyme solution contained a final concentration of 60 ng mL⁻¹ of JAK3. This enzyme solution was apportioned into Eppendorf reaction tubes in an ice-cooled rack. Dilution of the compounds was carried out in a two-step procedure. First, the 10 mM stock solutions of samples/reference were serially diluted in KB to a 100-fold excess of the final assay concentration via 10-fold dilution steps. As a second step of the dilution procedure, the respective volume of the 100-fold pre-dilutions was added to the JAK3 enzyme solution in Eppendorf reaction tubes. Thereby, final assay concentrations of samples and Tofacitinib were obtained.

It must be pointed out that vortexing of solutions containing JAK3 should be performed gently and only for few seconds as it significantly reduces the kinase activity leading to very shallow and non-sigmoid shaped inhibition curves.

Subsequently, all wells of the assay plate were rinsed three times with a PBS-containing wash bottle. Prior to the kinase reaction step, the remaining free binding sites were blocked by treatment with BB for 12 minutes at room temperature. After completion of the blocking step, the BB was discarded and the plate was rinsed three times with PBS containing 0.1% Tween-20 (polyoxyethylene (20) sorbitan monolaureate) (PBST) using a wash bottle. For draining, the plate was left upside down for 5 minutes on an absorptive surface. Potentially existing air bubbles originating from the washing step were removed by patting the assay plate carefully on a soft and absorptive surface. For the kinase reaction, 50 µL of the diluted samples and Tofacitinib were transferred from the Eppendorf reaction tubes to the corresponding wells of the assay plate. For positive control (STIM), indicating maximum phosphorylation, 50 µL of JAK3 solution were pipetted into the respective wells. For determination of NSB, 50 µL of plain KB were added into the respective wells. The pipetting of the kinase containing testing solutions to the assay plate was performed carefully but as quickly as possible (max. 5 minutes) since the degree of phosphorylation and therefore the detected kinase activity is time-dependent. During the kinase reaction, the plate was covered with a lid and incubated for one hour at 37 °C, gently shaking at 150 rounds per minute in the incubator. After the kinase reaction, the content of the plate was discarded. The plate was washed three times with PBST, drained and patted following the same procedure as described before.

While the plate was draining, the monoclonal anti-phosphotyrosine-peroxidase conjugated antibody was diluted 1 : 60 000 in BB which has been adjusted to pH 6.5. 100 µL of the antibody dilution were pipetted into all wells using an Eppendorf Multitette® plus equipped with a 5 mL Eppendorf Combitip plus®. For incubation of the antibody reaction, the plate was again covered with a lid and incubated as described for the kinase reaction step.

After the last mentioned incubation, the antibody solution was discarded and the assay plate was rinsed with PBST to remove any unbound antibody. The plate was again drained upside down on an absorptive surface and patted as described before.

Finally, 50 µL of the TMB substrate reagent were added into all wells using an Eppendorf Multitette® plus equipped with a
Adaption and optimization of the assay settings

The general protocol published by Lázaro et al. for the detection of protein tyrosine kinase activity was adapted to the specific requirements of the JAK3 kinase domain. As illustrated in the schematic ELISA procedure (Fig. 1), two kinase substrates, namely ATP and the synthetic polypeptide, are involved in the kinase reaction of this ELISA. Copeland et al. defined this kind of mechanism as a bisubstrate enzyme reaction. We could confirm the above-mentioned polypeptide to be a suitable substrate for this kind of kinase activity assay as it is recognized and sufficiently phosphorylated by JAK3. When defining conditions for kinase activity assays based on a bisubstrate reaction, the apparent \( K_m \) value for one substrate needs to be determined at the saturation concentration of the other substrate. As the assay will be carried out at the \( K_m \) value of ATP, the amount of polypeptidic kinase substrate adsorbed to the assay plate must be kept at the saturation concentration to avoid a limitation of potential phosphorylation sites. Consequently, a decreased signal magnitude will only be caused by a reduced kinase activity as a result of kinase inhibition by the kinase inhibitor. In contrast, the ATP concentration was kept at 100 mM for the determination of the required synthetic polypeptide concentration, to guarantee saturation of this substrate component. This time, the concentration of the polypeptide adsorbed to the assay plate was varied from 0.63 \( \mu \)g mL\(^{-1}\) to 100 \( \mu \)g mL\(^{-1}\). The signal magnitude measured using a 5 \( \mu \)g mL\(^{-1}\) polypeptidic kinase substrate was comparable to signal responses obtained with 10 \( \mu \)g mL\(^{-1}\) or 100 \( \mu \)g mL\(^{-1}\) of the afore-mentioned substrate (Fig. 2A). Thus, a concentration of 5 \( \mu \)g mL\(^{-1}\) of the synthetic polypeptide was considered as sufficient. In order to ascertain both, the optimal kinase concentration and the sensitivity of this ELISA method, the linearity of the relationship between signal and kinase concentration was determined. Concentrations between 15 ng mL\(^{-1}\) and 3840 ng mL\(^{-1}\) of JAK3 were incubated at an ATP concentration of 100 \( \mu \)M, to rule out that the kinase activity and the obtained signal magnitude were limited by ATP-depletion. In Fig. 2C, the OD\(_{450}\) is plotted as a function of the kinase concentration. For JAK3 enzyme concentrations up to 60 ng mL\(^{-1}\), the measured OD\(_{450}\) values are directly proportional to the applied kinase concentrations. Within this linear range, a decrease of kinase activity directly results in a proportional loss of the signal response. A further enhancement of JAK3 concentration does not result in a further proportional increase of analytical signal. Moreover, the employment of excessive kinase concentrations can diminish the sensitivity of such an assay system and thus disables the sufficient discrimination of small differences in inhibitory activity. A decrease of kinase activity by different inhibitor concentrations will not lead to a proportional reduction of the phosphorylation degree when applying excessive amounts of kinase. A linear regression of the optical densities corresponding to the respective kinase concentrations of the linear part of Fig. 2C was performed. The slope of the resulting regression line indicates the assay's sensitivity as a function of the kinase concentration. We determined a slope of 0.013 OD\(_{450}\) units per ng JAK3 * mL and a coefficient of determination (\( R^2 \)) of 0.982 proving the correlation between assay sensitivity and the kinase concentration. Since a concentration of 60 ng mL\(^{-1}\) JAK3 combines both, signal linearity and high signal magnitude, this concentration was considered as the optimal kinase concentration for this assay system.

The precision of this ELISA method employing a JAK3 concentration of 60 ng mL\(^{-1}\) was verified by a low standard deviation of 0.03 OD units.

In a subsequent step, the appropriate working dilution for the peroxidase-labelled monoclonal anti-phosphotyrosine antibody was investigated (Fig. 2B). Therefore, antibody dilutions were added to the wells with positive and negative controls to determine the respective maximum- and the NSB signal.
magnitude. NSB is caused by binding of the antibody to the non-phosphorylated polypeptidic kinase substrate or other interferents. An OD\textsubscript{450} below 0.1 was considered appropriate. The best signal-to-noise ratio was achieved with an antibody dilution of 1 : 60 000.

The \( K_m \) value for ATP was determined by titrating ATP concentrations between 0.1 \( \mu \)M and 1000 \( \mu \)M while keeping all other assay parameters constant (Fig. 2D). The rate of reaction in the presence of a large excess of ATP (1000 \( \mu \)M) was considered maximal and consequently de

\[ \text{IC}_{50} = \frac{1}{K_m} \]

and compound 1/2, \( \text{IC}_{50} \) values of 3.5 ± 0.6 nM (\( n = 18 \)), 154 ± 0.04 nM (\( n = 3 \)) and 311 ± 0.03 nM (\( n = 3 \)) were obtained. These \( \text{IC}_{50} \) values were compared with the \( \text{IC}_{50} \) values previously reported by Flanagan \textit{et al.}, even though it must be emphasized that direct comparison of \( \text{IC}_{50} \) values determined in different assays is precarious.44 However, \( \text{IC}_{50} \) values determined with our optimized ELISA correlate reasonably with those reported by Flanagan \textit{et al.} (Table 1).

In summary, the ELISA protocol established by Lázaro \textit{et al.} was transformed from an indirect to a direct format, as a second incubation step with a secondary detection antibody becomes redundant when the primary antibody is directly labelled with the detection enzyme. Moreover, potential cross reactivity arising from a secondary detection antibody that curtails the specificity of the ELISA response and therefore the accuracy of the readout data is avoided. Application of a single monoclonal antibody is less likely to cause interference with other than the target epitope. Apart from inter- and intra-assay signal consistency, non-specific signals are evaded and therefore the assay sensitivity and precision is improved.

Due to its sensitivity, this ELISA allows the investigation of SARs even within a series of structurally similar inhibitors.9

For exploration of selectivity, the extension to other members of the JAK family is conceivable in the same format. Furthermore, this assay protocol is suitable to be transferred to high-throughput screening campaigns using automated robotic instrumentation, making it applicable for the measurement of large numbers of samples at a time. Thus, it might also attract the attention of industrial researchers.

**Conclusions**

In the current report, we describe an optimized protocol for a direct JAK3 ELISA. Previously published non-cellular JAK3 assays apply radiometric formats or depend on multi-step procedures using expensive reagents or require special laboratory equipment. The advantages over existing protocols include easy performance, robustness, cost-efficiency and avoidance of radioisotopes. The assay is readily discriminating the effects of minor changes in the inhibitor structure on kinase inhibition and is thus suited for lead optimization. Essential instructions for successful establishment and handling of this ELISA are

| IC\textsubscript{50} ± SD | Literature IC\textsubscript{50} | Quotient IC\textsubscript{50}/IC\textsubscript{50} | IC\textsubscript{50} ± SD | Literature IC\textsubscript{50} | Quotient IC\textsubscript{50}/IC\textsubscript{50} |
|-----------------|--------------------------|------------------|-----------------|--------------------------|------------------|
| 3.5 ± 0.6\textsuperscript{a} | 1.0\textsuperscript{b} | 3.5 | 154 ± 0.04\textsuperscript{a} | 39\textsuperscript{c} | 3.9 |
| 311 ± 0.03\textsuperscript{a} | 160\textsuperscript{d} | 1.9 |

\textsuperscript{a} Mean ± SD (\( n = 18 \)). \textsuperscript{b} Mean ± SD (\( n = 3 \)). \textsuperscript{c} No SD values were given.
reported in detail. Unlike the general method reported by Lázaro et al., only one monoclonal anti-phosphotyrosine peroxidase conjugated antibody is required for detection, avoiding a second incubation time, cross reactivity and additional costs.

Abbreviations

| Abbreviation | Definition |
|--------------|------------|
| ATP          | Adenosine-5'-triphosphate |
| BB           | Blocking buffer |
| BSA          | Bovine serum albumin |
| DMSO         | Dimethyl sulfoxide |
| EMA          | European medicines agency |
| ELISA        | Enzyme-linked immunosorbent assay |
| FDA          | Food and drug administration |
| HEPES        | (2-[4-(2-Hydroxyethyl)piperazin-1-yl]ethanesulfonic acid) |
| ICH          | International conference on harmonisation of technical requirements for registration of pharmaceuticals for human use |
| IgG          | Immunoglobulin G |
| JAK          | Janus kinase |
| JAK3         | Janus kinase 3 |
| KB           | Kinase buffer |
| $K_m$        | Michaelis constant |
| LOD          | Limit of detection |
| NSB          | Nonspecific binding |
| OD           | Optical density |
| OD$_{450}$   | Optical density at 450 nm |
| PBS          | Phosphate-buffered saline |
| PBST         | PBS containing 0.1% Tween-20 |
| $R^2$        | Coefficient of determination |
| RA           | Rheumatoid arthritis |
| SARs         | Structure–activity relationships |
| TMB          | Polyoxyethylene (20) sorbitan monolaurate |
| $\gamma_c$   | Common gamma chain interleukin receptor (IL-2RG) |

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