

Comprehensive peptide mapping of protein therapeutics using the Biologics Explorer software

Streamlined workflows within the Biologics Explorer software for the characterization of biotherapeutic digests

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This technical note describes an introduction to the peptide mapping workflow templates within the Biologics Explorer software (v.1.0.2) along with some of their most common applications. Described are the key differences between the workflows that allow either quick assessment or in-depth investigation. In addition, an overview of the diverse tools for data visualization and interrogation is provided.

Peptide mapping continues to play an indispensable role in the development and quality control of biologics due to its ability to characterize, localize and quantify quality attributes. Differences in amino acid sequences and post-translational modifications (PTMs) induced by variations in manufacturing, purification and formulation of biotherapeutics can drastically impact their pharmacokinetics and pharmacodynamics profiles. The increasing complexity of biologics continues to pose significant challenges for their in-depth characterization. As such, novel and rigorous processing algorithms are essential to complement the continuous advancements at the sample preparation and LC-MS/MS fronts.¹⁻³

The Biologics Explorer software is the latest software suite from SCIEX for the comprehensive characterization of complex biologics, in intact or subunit forms, as well as protein digests. Data acquired using the state-of-the-art ZenoTOF 7600 system in either collision-induced dissociation (CID) or electron activated dissociation (EAD) mode can be processed. EAD allows for tunable electron energy, producing a varied fragmentation pattern that results in higher level of structural information. The Biologics Explorer software is an advanced software package powered by Genedata Expressionist algorithms, facilitating scientists to maximize the evidence-based information extracted from their rich LC-MS/MS spectra.

In this technical note, Biologics Explorer v.1.0.2 is used for the peptide mapping analysis of adalimumab as a model molecule. The advanced processing capacity of the software for sequence confirmation and identification of low or unexpected PTMs is demonstrated through examples. In addition, the functionality to

conduct and visualize comparative investigation is highlighted using samples with reduced and intact disulfide bonds.



Key features of the peptide mapping workflows within the Biologics Explorer software

- Streamlined and easy-to-use: Predefined processing settings, customized for SCIEX QTOF MS and MS/MS data, leverage an accelerated path for the optimization of biologics-specific data processing methods
- New depth of peptide mapping analysis: Distinct workflow structures support diverse analytical biotherapeutic applications, from discovery and development through to production and quality attribute monitoring. Four peptide mapping workflow templates are provided:
 - 1.PeptideMapping_Simple
 - 2.PeptideMapping_Extended
 - 3.PeptideMapping_Comparative
 - 4.PeptideMapping_ReviewSnapshots
- Evidence-based decision making: Traceability and transparency in data processing, visualization and review bring confidence and accuracy in decisions made with high efficiency

Methods

Sample preparation:

Reduced samples: adalimumab was denatured with 7.2 M guanidine hydrochloride in 100 mM Tris buffer (pH 7.2), followed by reduction and alkylation of cysteine bonds using 10 mM DL-dithiothreitol and 30 mM iodoacetamide, respectively. Protein digestion was performed with trypsin/Lys-C at 37°C for 16 h at pH 7.5. The reaction was stopped with 1% formic acid.⁴

Non-reduced samples: adalimumab was denatured with 7.2 M guanidine hydrochloride in 50 mM Tris buffer (pH 7.0). Free cysteine residues were capped with 5 mM iodoacetamide. Protein digestion was performed with trypsin/Lys-C at 30°C for 16 h at pH 7. The reaction was stopped with 1% formic acid.⁵

Chromatography: Detailed method parameters were described previously.^{4,5} Briefly, peptides from trypsin/Lys-C digests (5 µL, 2 µg) were separated with a CSH C18 column (2.1×100 mm, 1.7 µm, 130 Å, Waters) using an ExionLC AD system. Mobile phase A consisted of 0.1% formic acid in water, while the organic mobile phase B was 0.1% formic acid in acetonitrile.

Mass spectrometry: Data was acquired in positive ionization mode with a data dependent acquisition (DDA) method using the SCIEX ZenoTOF 7600 system. The electron energy for the alternative fragmentation in the EAD cell was set to 7 eV. Detailed method parameters were described previously.^{4,5}

Data processing: Data was processed with the Biologics Explorer software using different pre-built templates as discussed in the next sections.

Overview of the peptide mapping workflows

The Biologics Explorer software is prepackaged with 3 main and 1 supplemental peptide mapping workflow template with settings optimized for the processing of protein digests analyzed on SCIEX QTOF MS platforms, including the ZenoTOF 7600 system. All workflows share a common fundamental architecture, where activity nodes are arranged in a chronological order to process data sequentially followed by a *Review Results* activity node for the interrogation of the compiled results (Figure 1).

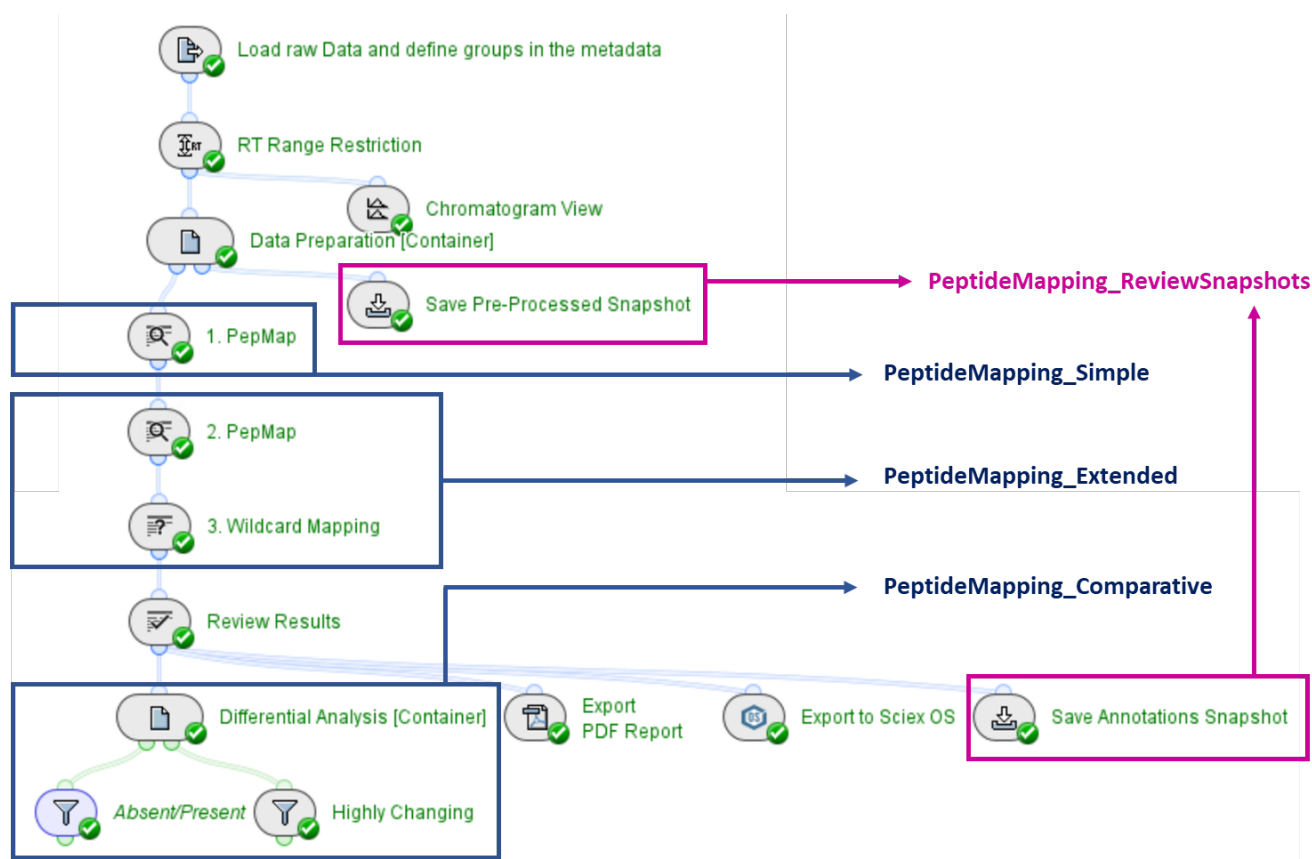


Figure 1. Layout of the PeptideMapping_Comparative workflow in the Biologics Explorer software v.1.0.2. Blue boxes highlight additional activity nodes within each workflow template that advance the in-depth characterization process. The pink boxes highlight activity nodes used to save intermediate data and results at different processing stages.

The advanced workflow structure established a stepwise approach to data processing with each activity node, maximizing the data quality and confidence for the peptide mapping stage. At first, noise reduction steps are applied to the data followed by detection of MS peaks, grouping of isotopic clusters, then further grouping of charge states and any additional associated adducts. Subsequent stages include MS/MS peak consolidation and detection, plus deisotoping of MS/MS peaks to further maximize confidence and robustness in the following stages where data is matched to amino acid sequences in *in silico* for peptide identification and PTM characterization.

The results of each activity node can be visualized independently, whereas data across the contained tables and figures are automatically connected. In addition, results visualization can be synchronized across different activity nodes enabling efficient review during the data processing and analysis stages.

The 3 main 'PeptideMapping' workflows (_Simple, _Extended and _Comparative) are designed with an increasing level of complexity to suit different depths of peptide mapping investigations (Figure 1). All workflows contain an *Export PDF Report* activity node, where different sections of the generated report can be customized to include specifically selected or all

input/output details for each activity node. The generated PDF report file can be downloaded and encompasses 2 attachments by default. The first attachment is an excel file of results, which can be tailored as per personal preference for the depth of its contents. The second attachment is a copy of the executed workflow. This .xml file can be effortlessly opened by dragging and dropping it into the workflow preview pane of the software. This is a substantially efficient feature, particularly if workflows are intended to be shared among users, different groups or sites, or revisited at a future timepoint.

All main workflows are also equipped with an *Export to Sciex OS* activity node, where a tailored .txt list of product quality attributes (PQA) or critical quality attributes (CQA) can be generated and exported to the Analytics portion of SCIEX OS software for performing further multi-attribute methodology (MAM) analysis.

PeptideMapping_Simple workflow

This workflow is designed to provide a quick and efficient peptide mapping overview, for quality checks or during early process development stages. It is suited for assessment of sequence coverage and characterization of common PTMs, including N-linked glycans, which can be identified using the glycan libraries provided with the Biologics Explorer software.

DDA-based MS/MS methods are common practices in peptide mapping. Depending on the user-defined settings for DDA, multiple MS/MS events can be expected from a single precursor ion. The *MS/MS Consolidation* activity node is set by default to merge multiple MS/MS events to a single spectrum per isotopic cluster (Figure 2). This integration of fragmentation data maximizes the evidence for high confidence peptide identification and reduces both false negatives and false positives events. Within the same activity node, the MS/MS data is further merged *Across Chromatograms*, with the option to deselect the merging process depending on the sample set and objective of the analysis (Figure 3). If this merging option is selected, the algorithm will consolidate MS/MS spectra for the same feature across the entire sample set and the resulting consolidated MS/MS will be assigned to the sample with the highest intensity MS/MS spectrum. This capability leverages the information from individual spectra to amplify the evidence of peptide fragmentation and generates an enhanced single spectrum for confident and efficient peptide identification. As such, the time needed for manual data evaluation in the *Review Results* activity node can be substantially reduced.

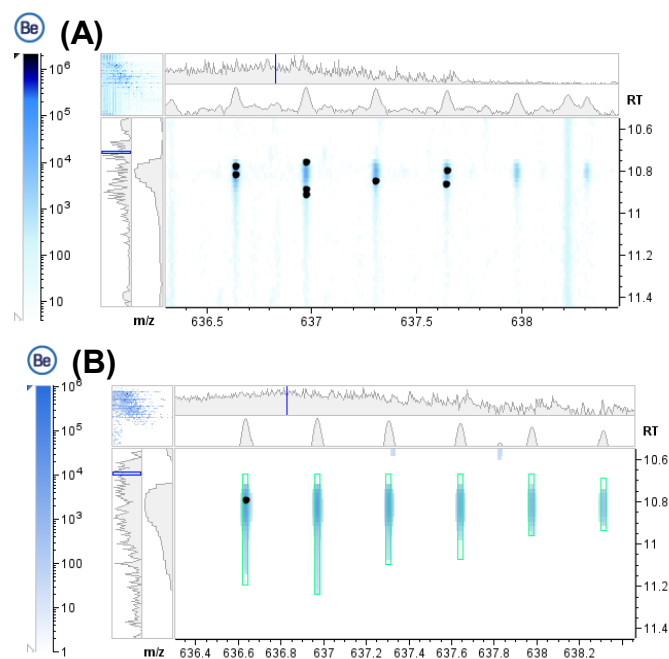
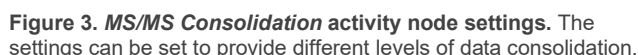


Figure 2. Synchronized and zoomed RT and m/z regions of the ion map. Load Raw Data (A) and MS/MS Consolidation (B) activity nodes, demonstrating a peptide cluster with multiple and consolidated MS/MS triggers (black dots), respectively.

The Biologics Explorer software is prepackaged with 3 cumulative CHO N-glycan libraries of increasing complexity and diversity to support various applications, where the largest library contains 136 N-glycans. Additionally, over 26,000 N-glycans



(C)

(D)

Name	Ann...	Intensity	Flags	m/z
Peak_621	9	13.0000 [G]		1115.4472
Peak_794	8	61.0000 [G]		2708.0522
Peak_773	3	40.0000 [G]		2688.2369
Peak_794	2	1584.0000 [G]		3050.2811
Peak_319	1	226.0000 [G]		145.1006
Peak_115	1	87.0000 [G]		185.1311
Peak_130	1	165.0000 [G]		191.1790
Peak_155	1	59.0000 [G]		205.1599
Peak_167	1	65.0000 [G]		209.1305
Peak_188	1	72.0000 [G]		220.1830
Peak_193	1	29.0000 [G]		232.1115
Peak_195	1	29.0000 [G]		223.1453
Peak_212	1	43.0000 [G]		239.1794
Peak_263	1	21.0000 [G]		251.1678
Peak_387	1	42.0000 [G]		269.2234
Peak_326	1	13.0000 [G]		834.2749
Peak_378	1	31.0000 [G]		873.4181
Peak_633	1	26.0000 [G]		1176.4021
Peak_633	1	200.0000 [G]		119.0619
Peak_379	1	157.0000 [G]		344.2306
Peak_454	1	181.0000 [G]		500.3287
Peak_484	1	166.0000 [G]		629.3294
Peak_498	1	200.0000 [G]		758.4117
Peak_630	1	144.0000 [G]		1049.3230
Peak_775	1	51.0000 [G]		2692.2529
Peak_201	1	77.0000 [G]		102.0466
Peak_171	1	32.0000 [G]		212.1493
Peak_172	1	71.0000 [G]		213.1657
Peak_211	1	37.0000 [G]		230.1497

Row	Fragment	Adduct	Charge
Peak_633	B	H+H	1

Row	Peak_633
Fragment	B
Glycan	
Adduct	H+H
Charge	1
Calc. Mass	1175.3963
Calc. m/z	1176.4036
m/z Delta	-0.0008
m/z Delta [ppm]	-69.96

p 4

(A)

Peptide	Modifications	Mod. Locations	Calc. Mass ¹	Flags	RT	Delta	Consolidated Score
TPEVTCVVVDVSHEDPEVKFNWYVDGVEVHNAK	(-18.010208), Carbamidomethyl	[D284] [C265]	3778.7941	W	23.7103		274.0780
TPEVTCVVVDVSHEDPEVKFNWYVDGVEVHNAK	Carbamidomethyl	[C265]	3796.8043		23.1121	-0.0034	402.7700

(B)

Peptide	Modifications	Mod. Locations	Calc. Mass ¹	Flags	RT	Delta	Consolidated Score
TPEVTCVVVDVSHEDPEVKFNWYVDGVEVHNAK	Carbamidomethyl, Dehydrated	[C265] [D284]	3778.7937		23.7103	0.0004	274.0780
TPEVTCVVVDVSHEDPEVKFNWYVDGVEVHNAK	Carbamidomethyl	[C265]	3796.8043		23.1121	-0.0034	402.7700

Figure 5. Representative example for identifying unspecified modifications using Wildcard Mapping activity node. (A) Peptide: TPEVTCVVVDVSHEDPEVKFNWYVDGVEVHNAK identified by *Wildcard Mapping* to be modified with a loss of -18.010 Da from aspartic acid residue. (B) TPEVTCVVVDVSHEDPEVKFNWYVDGVEVHNAK, with a confirmed dehydration modification from aspartic acid residue following the addition of the modification in 2. *Pepmap*.

PeptideMapping_Extended workflow

The PeptideMapping_Extended workflow has 2 additional activity nodes, 2. *PepMap* and 3. *Wildcard Mapping* (Figure 1). It has been optimized for the analysis of more complex proteins and in-depth peptide mapping characterization. As an example, a more comprehensive glycosylation analysis is possible if the 1. *PepMap* activity node is used to identify the usually higher-abundance N-linked glycopeptides present in the sample and the 2. *PepMap* activity node is used for O-glycan mapping, using either the prepackaged or a customized O-glycan library. By default, the 2. *PepMap* activity node ignores the features annotated in the prior node, reducing the computational search space and the rates of false positive matching. Nonspecific digestion, conjugates (either entered as molecular formulae or delta loss/gain value) and less common PTMs can be also specified within 2. *PepMap*.

Wildcard Mapping is a powerful tool designed for discovery purposes where unexpected modification, that are not specified in the processing parameters, are detected under very stringent acceptance criteria. If not required, this activity node (as with others) can be skipped by activating the 'bypass' icon associated with the activity node itself. In the following sections an example is given. Here, an expected chemical modification was used as an example to demonstrate how *Wildcard Mapping* can be used to identify and confirm unexpected modifications within a biologics-specific processing method.

The analysis of the *Wildcard Mapping* results from the _Extended workflow revealed peptides with an average loss of 18.010±0.005 Da from aspartic acid residues. Using the Modifications Editor tool as a guide to identify possible matches, this PTM could be attributed to the loss of a water molecule arising from nucleophilic attack on the side chain carbonyl

carbon of aspartic acid during isomerization, resulting in the formation of succinimide intermediate.⁶ The next stage following the detection of an unexpected modification is collecting MS and MS/MS evidence. To investigate this representative example further, a selected peptide, TPEVTCVVVDVSHEDPEVKFNWYVDGVEVHNAK, exhibiting the detected mass loss from position D25 was compared to its native form (Figure 5A). A mass shift of 3.601 Da between the monoisotopic peaks of the 5+ charge state of the modified and unmodified peptides is consistent with H₂O loss (Figure 6). Additionally, the slightly longer retention time of the modified peptide correlates with the expected increase in hydrophobicity relative to the unmodified D25 peptide (Figure 6).

Investigation of the 3D plot of the 5+ charge state of the modified peptide further highlights its chromatographic resolution from other closely eluting peaks (Figure 6). Finally, the modification was confirmed on the MS/MS level, using the consolidated and deisotoped MS/MS spectrum of the 5+ charge state of the modified peptide to reveal a c- and z- ion ladder consistent with 18.010 Da loss from D25, thus providing unequivocal confirmation on the location and type of the modification (Figure 7). With this sufficient evidence generated for the existence of a dehydration event from aspartic acid residue, the 2. *Pepmap* activity node was reset and that modification was entered as an additional variable modification into the search parameters. The result (Figure 5B) shows that the modified peptide was identified with a high consolidated score and a low mass error (0.0004 ppm). Using the same logic, modifications that are unexpected for a specific sample set can be identified and confirmed on MS and MS/MS levels resulting in deeper characterization of the investigated molecule and better optimization of the biologics specific workflow for future routine analysis.

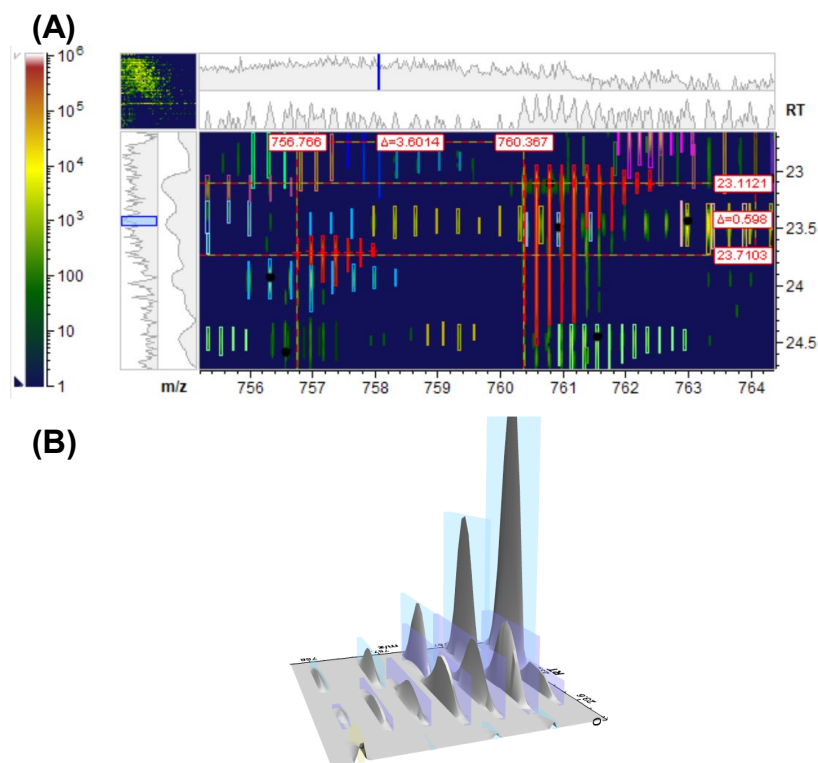


Figure 6. Visualization of the 5+ charge state of the modified peptide TPEVTCVVVDVSHEDPEVKFNWYVDGVEVHNAK. Ion map view (top) and 3D view (bottom) of the peptide identified through *Wildcard Mapping* provide further information. Measuring the distance between the modified and unmodified forms in the ion map (red and white bars) can be used to confirm the observed modification, while the 3D plot can detect interferences not visible from the 2D view.

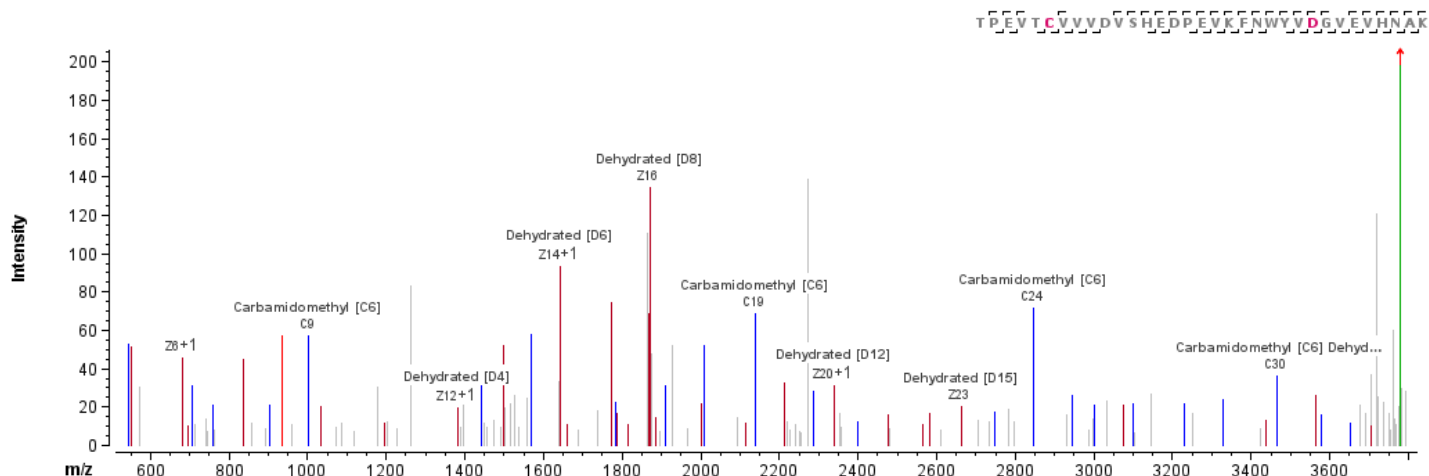


Figure 7. Consolidated and deisotoped MS/MS spectrum of the 5+ charge state of the modified peptide TPEVTCVVVDVSHEDPEVKFNWYVDGVEVHNAK demonstrating several C and N termini fragments that support D25 modification.

PeptideMapping_Comparative workflow

The _Comparative workflow is further empowered with dedicated statistics activity nodes for differential analysis (Figure 1). Samples exposed to different stress conditions or sample preparation steps, those acquired during instrument optimization or process development, different lots or manufacturers and how they can efficiently be analyzed using the _Comparative workflow.

Sample groups can be specified within the metadata editor either in *Load Raw Data* or in *Data Setup* activity node. The *Highly Changing* activity node allows monitoring of the fold change in peptide abundance between samples, where a minimum threshold for fold change can be set depending on the nature of the samples. The *Absent/Present* activity node on the other hand can be used to investigate new peaks detected in at least 1 sample group (Figure 1). The output results from each activity node are compiled in interactive tables that provide comprehensive details on each identified peak. Furthermore, the data can be synchronized with any of the previous activity node(s) to facilitate traceability. To demonstrate this feature, reduced and non-reduced adalimumab samples were run in the _Comparative workflow template. Peptides with cysteine carbamidomethylation in the former group and peptides with intact disulfide bridges in the latter group were observed, as expected for these samples (Figure 8).

PeptideMapping_Review Snapshots workflow

Finally, this workflow (Figure 9) is designed to open 2 types of snapshots files (.sbf) that correspond to either intermediate (such as, partially processed) data or reviewed (for example, annotation) results generated from the main peptide mapping workflows (Figure 1). To quickly view fully processed and reviewed results, the annotated snapshots can be opened in the racetrack *Review Results from Same Batch* (Figure 9). On the other hand, partially processed snapshots can be opened in the racetrack *Review Results from Different Batches* (Figure 9). As such, the same processing parameters and peptide mapping settings can be applied to all samples concurrently. In general, snapshots enable faster analysis times since the contained data is either partially or completely processed prior to being saved as .sbf files. Snapshots also provide a useful means of storing data with a lower memory footprint for further inspection later.

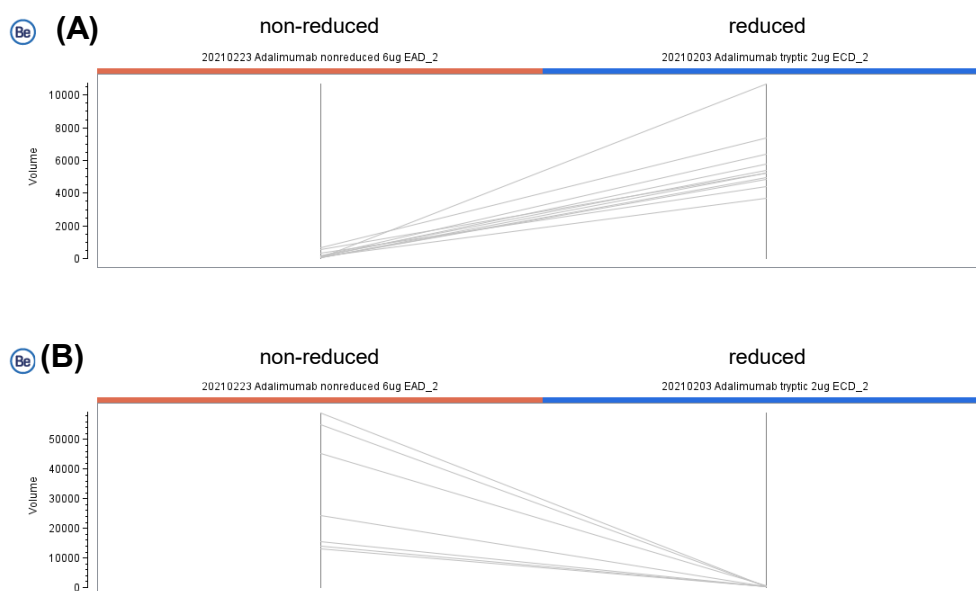


Figure 8. Example plot from the *Highly changing* activity node. The results are demonstrating a profile plot of representative peptides that are at least 10-fold different in abundance between reduced and non-reduced adalimumab samples, due to different sample preparations. Carbamidomethylated peptides are highly abundant in reduced samples but not present in the non-reduced samples (A), while peptides with intact disulfide bonds are present in the non-reduced samples and not in the reduced samples (B).

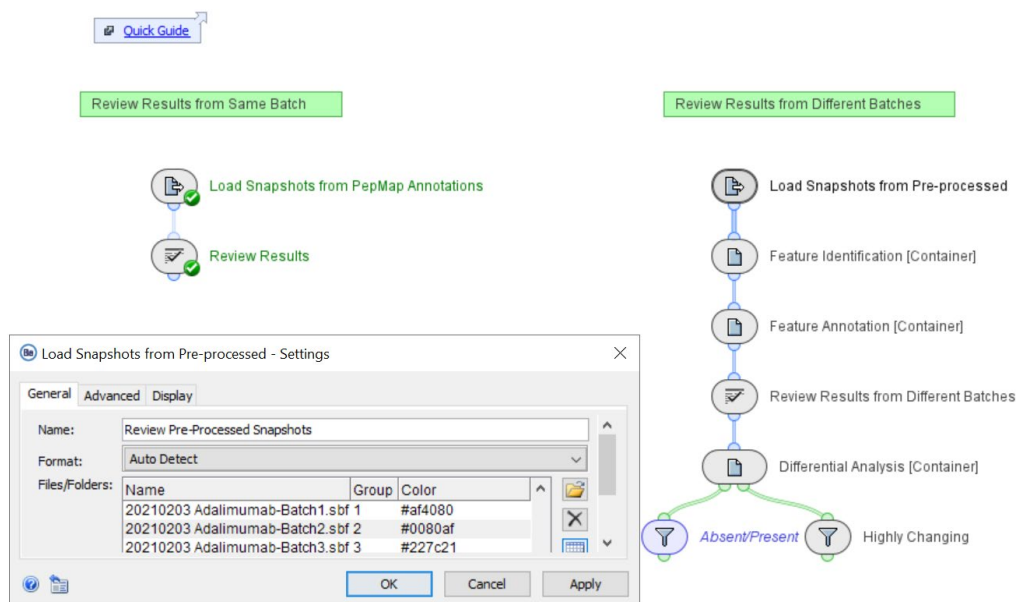


Figure 9. Layout of the PeptideMapping_ReviewSnapshots workflow in the Biologics Explorer software v.1.0.2. Two racetracks are included to either inspect previously analyzed and annotated results (left track), or to combine pre-processed data for a differential analysis across different batches (right track).

Conclusion

- Workflows with optimize settings maximize the efficiency by which high-quality peptide mapping evidence can be extracted from rich LC-MS/MS data (EAD or CID fragmentation)
- Diverse workflow structures allow for the flexibility to fit various needs while developing or manufacturing biotherapeutics
- Various options available for saving, sharing, reporting and exporting results provide a robust platform for routine high-throughput analysis meeting diverse needs along the pipeline of biologics development

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