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The Skyline Ecosystem: Informatics for Quantitative Mass Spectrometry Proteomics

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Abstract

Skyline is a freely-available, open-source Windows client application for accelerating targeted proteomics experimentation, with an emphasis on the proteomics and mass spectrometry community as users and as contributors. This review covers the informatics encompassed by the Skyline ecosystem, from computationally-assisted targeted mass spectrometry method development, to raw acquisition file data processing, and quantitative analysis and results sharing.

Keywords

targeted proteomics; quantitative mass spectrometry; informatics

I. Introduction

Since the completion of the Human Genome project (Consortium 2001; Venter et al. 2001; Consortium 2005), a wealth of functional genomic techniques have emerged as the focus of research shifts to assigning function and understanding the regulation of each of the identified gene products. The focus of these efforts is to better understand how the information stored in a genome encodes all the complexity necessary to sustain a complex multicellular organism (Lander 2011). Notwithstanding impressive gains in these technologies, interpretation of their results is limited without corresponding data on proteins, the primary functional macromolecules encoded by the genome. This limitation is highlighted by the observation that measurements performed at the nucleic acid level tend to correlate very poorly with those performed at the protein level (Greenbaum et al. 2003; Schrimpf et al. 2009), especially in cases when experimental noise is not considered (Csardi et al. 2015). A combination of factors likely contribute to the poor protein-transcript correlation, including the variable lifetime of each protein dictated by its respective synthesis and degradation rates; the existence of multiple different forms of each transcript product due to post-translational modifications; and finally, the temporal/spatial regulation imparted by protein complexes and the highly compartmentalized nature of cellular processes.

Accordingly, the direct analysis of proteins, albeit more technically challenging, is absolutely crucial to a complete understanding of gene regulation and systems biology.

A. Introduction to quantitative mass spectrometry proteomics

To meet these ends, tandem mass spectrometry (MS/MS) has emerged as the dominant analytical platform for the direct characterization of the protein fraction from complex biological matrices (Ong and Mann 2005). To date, a majority of mass spectrometry-based proteomic workflows have utilized a “bottom-up” approach in which proteins are digested with an endoprotease prior to analysis. The resulting peptide mixture is typically separated via nano-flow reverse-phase liquid chromatography, ionized, and emitted directly into a mass spectrometer for analysis.

Both absolute and relative quantitative measurements, reviewed in detail elsewhere (Ong and Mann 2005), are possible via several of the commonly applied MS acquisition methods. Targeted acquisition methods, including selected reaction monitoring (SRM) (Picotti and Aebersold 2012), also known as multiple reaction monitoring (MRM) (H. Zhang et al. 2011), and parallel reaction monitoring (PRM) (Peterson et al. 2012), quantify peptides from a preprogrammed list of precursor-fragment pairs and scheduled isolation windows based on previously-determined chromatography elution times. Data-independent acquisition (DIA) (Venable et al. 2004) such as Sequential Window Acquisition of all Theoretical Fragment ion spectra (SWATH) (Gillet et al. 2012) forgo preprogrammed precursor-fragment pairs, widening the isolation windows to activate all ions in a pre-specified mass-to-charge (m/z) range. (A detailed review of DIA methodology can be found elsewhere (Chapman, Goodlett, and Masselon 2014; Bilbao et al. 2015), including peptide-centric approaches to DIA (Ting et al. 2015).) It is also possible, through MS1 filtering informatics techniques (Schilling et al. 2012), to use data dependent acquisition (DDA) for quantitative analysis as opposed to conventional detection analysis.

The type of acquisition influences the selectivity, reproducibility, repeatability, limit of detection, dynamic range, and data density of the assay (Domon and Aebersold 2010). Additionally, acquisition type places specific requirements on assay development and influences the computational strategy for analyzing data. A variety of individual informatics tools have been developed to aid in assay development and to process the data collected with various acquisition types, reviewed elsewhere (Cham, Bianco, and Bessant 2010; Colangelo et al. 2013). Many freely available informatics tools, however, struggle with community adoption, due to issues with limited end user design, and lack a complete pipeline spanning method development through data analysis for an experiment.

B. Overview of the Skyline ecosystem for quantitative mass spectrometry informatics

Properties such as easy access, large dataset management, integration with other commonly used tools, intuitive data visualization, timely issue resolution, documentation, support, as well as facilitated sharing of data files and the methods used to collect them (Codrea et al. 2007) are important aspects that influence software adoption. With these needs in mind, the freely-available and open-source Skyline ecosystem was developed with a user-friendly interface, comprehensive file compatibility, vendor-neutral data processing, intuitive

visualization, and reasonable computational requirements (MacLean et al. 2010). The original objective of the Skyline project was to create a single informatics tool to generate MS methods and to analyze the data collected for chromatography-based quantitative MS experiments. In addition to these core functions, Skyline now invites the community to share their own informatics tools through an external tool store (Broudy et al. 2014) for software tools that support point-and-click installation and can be run from the Skyline Tools menu. Furthermore, the introduction of additional software to the Skyline ecosystem such as Chorus for sharing raw MS files (<http://chorusproject.org>) and Panorama for sharing Skyline processed experimental results (Sharma et al. 2014), has helped facilitate large-scale MS datasets and inter-laboratory collaborations.

The Skyline ecosystem is unique among freely-available, open source mass spectrometry proteomics software in its end-to-end support of the targeted proteomic mass spectrometry workflow. A Skyline document is first used for assay development, aiding in instrument method creation for targeted and DIA experiments (Figure 1). Skyline exports the methods for use in mass spectrometry acquisition on a broad range of instruments from 6 different mass spectrometer vendors (Table 1). Without need of any file conversion, Skyline then supports importing raw data from most LCMS capable instruments, calculating peak areas in a vendor-neutral manner. Peak area data may be explored within the Skyline document using core analyses, comparing peptide retention times, peak areas, sample groups, underlying chromatograms and even mass spectra when available. Further analyses are possible, including those made available by external tools integrated into the Skyline ecosystem and through data report exports that researchers can process using their own tools, and custom code in R, MATLAB, Python, etc. Although a freely-available, open source academic project, Skyline's engineering includes rigorous nightly testing to ensure any code changes made during the day are compatible with the program's many other various functions. This level of thoroughness ensures the mass spectrometry community receives an informatics toolkit that is consistent and highly maintained, allowing researchers to upgrade with confidence as the software is adapted and changed.

Today, over 8,700 mass spectrometrists are registered Skyline users with more than 64,000 installations since first public release, and over 1,100 publications have cited the original Skyline paper. We next describe how the community uses the Skyline ecosystem, and the informatics employed by the Skyline ecosystem, from assay development, to data processing and visualization, and finally dissemination of results.

II. Assay development

The requirements for developing an effective quantitative MS proteomics assay are specific to the type of experiment and the peptide targets being assayed. For all experiments, prior to MS acquisition, it is obligatory to create a program for the instrument that defines the instrument parameters and defines how the data is to be collected by the instrument. In addition, depending on the acquisition mode of the instrument (i.e., SRM/MRM, PRM, DIA and DDA), multiple decisions must be made to optimize the acquisition of the data (Figure 1). For example, the experiments with the most intensive assay development, scheduled SRM/MRM and PRM type experiments, necessitate selection of target peptides and their

transitions (SRM only) prior to acquisition, validation of transitions by MS/MS spectra, potentially optimization of individual parameters (such as collision energy - CE) and determination of retention times (RT) for optimal MS instrument scheduling. On the other hand, for DIA experiments, the only required step pre-acquisition is calculating isolation window schemes. Although this review is focused on the Skyline ecosystem for quantitative proteomics, we note that the ecosystem also works for generalized small molecules (Tang et al. 2015) and briefly describe considerations for non-peptide targets. In this section, we describe the steps required for assay development, noting which steps are necessary for which experiment types.

A. Peptide and transition selection for targeted experiments

Many proteomics hypotheses are rooted in biological observations, and so selecting proteins of interest and peptides that are exclusively representative of those proteins is often the first experimental design step in targeted bottom-up proteomic experiments, such as SRM/MRM and PRM. Selection of peptides for targeted assays is a complex process, involving consideration of (1) specific peptides or amino acid modifications of interest, (2) biological influences on the protein of interest, (3) chemical influences on peptide suitability for MS experiments, and (4) for SRM/MRM experiments, the selection of fragment ions for quantitation.

1. Specific peptides or amino acid modifications of interest—In the first case, specific amino acid modifications, especially post-translational modifications at the protein level, may dictate a peptide sequence of interest. This is especially seen in targeted phosphoproteomics assays, where the phosphosite of interest has previously been determined by prior experiments (Schilling et al. 2012, Sherrod et al. 2012, Abelin et al. 2016). In these cases, it may be easiest to manually enter the peptide sequences of interest. Skyline accepts peptides added directly to the document as lists in the Targets window. Peptides added as lists may have modifications and even charge states specified in the added sequence text. They may also be modified manually within Skyline one at a time, or in bulk by changing the Skyline modification settings.

2. Biological influences on the protein of interest—For situations where the peptide sequence is not defined by the experiment, Skyline accepts lists of proteins, either entered manually, copy-pasted, or as a FASTA file import. After proteins are added to the document, Skyline digests the proteins *in silico* to generate a list of peptides. The result of Skyline's *in silico* digestion depends on the particular endoprotease specified in the settings of the Skyline document. The most common endoproteases used in bottom-up proteomics are Lys-C, which hydrolyzes specifically at the carboxyl side of lysine; chymotrypsin, which cleaves amide bonds on the carboxyl side; and trypsin, which cleaves the carboxyl side of lysine or arginine. Other Skyline Peptide Settings that affect results of peptide list generation are common biochemical sample preparation concerns such as missed cleavages, oxidized methionine, and peptide amino acid length (Anderson and Hunter 2005; Lange et al. 2008; Prakash et al. 2009). After endoprotease(s) are selected and biochemical considerations are defined in the Peptide Settings in the Skyline document, researchers can add proteins of

interest to the Skyline target list and Skyline automatically performs *in silico* digestion on the proteins and the resulting peptides displayed, organized by protein of origin.

A point of consideration for proteomics research with clinical applications is the selection of peptides that may have naturally occurring amino acid variations due to individual subjects' genetic backgrounds. Single nucleotide polymorphisms (SNPs) in the genome may give rise to amino acid changes in the final proteoform, which may alter a peptide sequence. To help guide users collecting data on clinical samples that may include SNP-related variation, Skyline provides users with access to the informatics tool Population Variation (Fujimoto et al. 2014). Population Variation reveals all human sequence variation within a set of user-specified peptides or proteins by identifying the minor allele frequency of peptide targets. The tool then filters SNP data records from dbSNP by criteria directly relevant to proteomics experiments, storing entries with minor allele frequency > 0.01, a non-null protein accession, and a protein-influencing mutation (missense, stop-gain, frameshift). The refined list is stored as a SQLite database and can be accessed through a Skyline plug-in. Running the Population Variation Skyline plug-in outputs a table listing the isoforms and peptide variants for all proteins included in the Skyline document. Researchers can use this output to consider variant peptide targets to ensure that the assay accurately measures.

3. Chemical considerations of selected peptides—Next, the hypothesis-based, biologically considered peptides must be validated for chemical considerations, namely MS signal robustness. Peptides from the same protein of interest have a range of MS signal response, with some peptides reliably responding strongly and others responding weakly or variably to MS conditions (Kuster et al. 2005). These widely ranging responses are dictated by sequence-specific physiochemical properties (e.g., length of the amino acid sequence, charge, presence of various amino acids, and hydrophobicity) and can be empirically determined using prior knowledge from MS experiments (Stergachis et al. 2011) or by using predictive algorithms.

Empirical determination of high-responding peptides requires performing preliminary MS experiments with the potential targets, often synthesized or purchased, in the intended sample matrix (Stergachis et al. 2011). The mass spectrometrists then evaluate the potential target peptide and transition pairs for signal response and chemical noise interference. Skyline facilitates this empirical evaluation with simple transition deletion and addition tools, including ability to Undo these operations, allowing researchers to easily create or modify transition lists for targeted assay development. Besides empirical determination, however, it is also possible to query past MS experiments to evaluate peptide signal response, making use of Skyline-supported online repositories like PeptideAtlas (Desiere et al. 2006), Human Proteinpedia (Mathivanan et al. 2008), GPM Proteomics Database (Craig, Cortens, and Beavis 2004), and PRIDE (Jones et al. 2008). A caveat to using repositories, as opposed to an assay-specific preliminary experiment, is that peptide response is not the same across instruments and acquisition types.

In addition to empirical determination, predictive algorithms provide an alternative or complementary method to select the target peptides most likely to be high-responding for a set of proteins (Mallick et al. 2007; Fusaro et al. 2009; Eyers et al. 2011; Muntel et al. 2015).

For researchers interested in using predictive algorithms for SRM/MRM and PRM peptide selection, Skyline has implemented the publically available, open-source PREGO algorithm Searle et al. (2015) as a plug-in. PREGO (Searle et al. 2015) predicts high responding peptides using an artificial neural network on DIA experimental data. The artificial neural network was trained using 11 minimally redundant, maximally relevant physiochemical properties that describe peptide size, structure, and hydrophobicity. PREGO outperforms previous predictive algorithms, correctly predicting more high-responding peptides than other algorithms. This performance improvement is believed to stem from a more representative training set. As mentioned above, peptide signal response differs between instruments and acquisition types. PREGO, being trained on a DIA dataset, may perform better because peptide signals in DIA datasets better represent peptide signals in SRM datasets. An important note is that these predictive algorithms mentioned above do not predict transition signal response, only peptide response.

The final number of peptides required for a quantitative assay depend on the analytical rigor of the experiment, the details of the project, and the purpose. A description of these considerations and their implications on assay development is described elsewhere (Carr et al. 2014).

4. Selection of transitions for SRM/MRM experiments—By definition of the method, all transitions for a precursor are measured for a PRM experiment, and therefore PRM experiments do not require selection of fragments prior to acquisition. However, SRM/MRM experiments target only the transitions preprogrammed for acquisition. Selection of optimal transitions is critical for quantitative experiments, as poorly designed assays will suffer unreliable, inaccurate, or nonspecific quantitation (Ludwig et al. 2012).

It is common to choose *y*-type ion fragments, due to high ion abundance compared to the alternative, *b*-type ion fragments (Holstein (Sherwood), Gafken, and Martin 2011). Similar to peptide selection, transition selection must be evaluated for chemical considerations, namely transition MS signal response and transition selectivity. Transition signal response may be assessed empirically through preliminary MS experiments to evaluate potential transitions in the appropriate experimental sample matrix and under the experimental instrument conditions. The mass spectrometrists must manually confirm that the transitions are high-responding and free of interference, and remove any transitions that do not meet those criteria. Alternatively, predictive algorithms for thermodynamic peptide fragmentation (Z. Zhang 2004; Z. Zhang 2005) may provide computationally-assisted transition selection, and computational tools have been designed to aid in SRM method development (Röst et al 2012), though none have been integrated with Skyline yet.

Current standard practice (Carr et al. 2014) monitors three or more transitions per peptide to make a reliable quantitation. However, statistically, if the transition has been evaluated as high-responding and free of interference, it is possible to perform quantitative analysis on one transition, using the other monitored transitions for confirming the identity of the peptide precursor.

B. Retention time determination for scheduled MS experiments

Most quantitative mass spectrometry experiments hyphenate reversed-phase high performance liquid chromatography (RP HPLC) to separate and simplify complex proteomic samples. Coupling LC to MS adds a time dimension to the data, as peptides elute off the solid-state column at a particular time in the chromatographic gradient. As with other modes of reversed phase chromatography, LC-MS peptide RT is dependent on several experimental factors, such as the physiochemical properties of the target peptide itself; background matrix of the sample; column-specific details including stationary phase material, bed length, and temperature; and the chromatography details including gradient percentage and delivery speed (Moseley et al. 1991). In the case of liquid chromatography coupled SRM/MRM and PRM experiments (LC-SRM/MRM, LC-PRM) on triple-quadrupole mass spectrometers, the number of peptide precursor-fragment transitions to be measured may exceed the speed at which the instrument can measure them and still maintain a cycle time appropriate for quantification (2–3 seconds per cycle maximum). In these cases, “scheduling” methods enable measurements of tens to hundreds of individual peptides, by allowing only a subset of the targeted peptides to be measured in any given cycle. The acquisition schedule for these methods includes precursor m/z , transition m/z , and the RT, or time window during which the precursor peptide elutes off the LC column.

Skyline’s ecosystem incorporates several complementary tools to predict peptide RT. The first, SSRCalc (Krokhin 2006; Spicer et al. 2007), is based on calculated hydrophobicity, as determined from the peptide amino acid sequence, to predict a peptide RT. This approach is particularly useful when empirical RT is unknown for a peptide. Alternatively, when peptide RT has been previously observed, a standard set of reference peptides can be used to calibrate RT prediction for any number of target peptides of interest on new columns or chromatography methods. In this approach, termed indexed retention time (iRT) (Escher et al. 2012), the reference peptides act as anchor points across a range of hydrophobicities, allowing the HPLC run-time to be calibrated and the assay-specific peptides to be aligned to the observed iRT reference peptide anchors. The iRT method is particularly useful in interlaboratory and large-scale experiments, projects which typically necessitate use of multiple LC systems and columns. For these projects, the iRT workflow integrated into Skyline provides a simple method to transfer chromatography empirical knowledge from one system to another, or to easily transition to a new column when the previous is replaced.

After predicting peptide RT through either method, or simply by using prior measurements that have already been imported, Skyline can export an acquisition table including all relevant information for a scheduled LC-SRM/MRM or LC-PRM method, including start and end times for peptide elution. The priority for these experiments is to capture the entirety of the chromatogram peak as the peptide elutes from the column, but with as narrow a window as possible. The mass spectrometer is limited in the number of peptide precursors it can measure at any given time, as dictated by the speed of the instrument (duty cycle), and the number of transitions to measure at that time, as dictated by predicted RT and the width of the scheduling time window. In order to assay as many peptides as possible, it is necessary to adjust the scheduling windows to reflect the instrument’s speed and the number of transitions eluting at each time point. Skyline facilitates this adjustment with a

visualization option in the retention time pane that displays the number of transitions eluting over the chromatographic gradient under several potential scheduling window widths.

C. Instrument parameter optimization

Determining the optimal set of MS instrument parameters for a targeted experiment is necessary in order to create an effective assay. One parameter of particular importance to targeted experiments is collision energy (CE). Optimized CE increases fragment ion intensity, which confers stronger, more reliable signal response (Sherwood et al. 2009). Computational estimation of optimal CE based on precursor m/z and a simple linear equation (Equation 1) is useful for both triple quadrupole (Picotti et al. 2010) and quadrupole time-of-flight instruments (Griffin et al. 1991; Prakash et al. 2009). An automated pipeline for optimizing CE specifically for quantitative assays is integrated in Skyline to achieve maximum fragment ion intensity (MacLean et al. 2010) and therefore strongest, most reliable signal response for the peptides in the assay. Recent versions have added the ability to store optimized parameter values in a library for future re-use and easier sharing.

Equation 1

Generalized equation for predicting optimal collision energy.

$$\text{Collision Energy} = k \left(\text{precursor } \frac{m}{z} \right) + b$$

D. MS/MS spectral library creation

Although not strictly required for assay development, inclusion of spectral libraries in quantitative proteomics aids in downstream data processing. In spectral library searching, spectra acquired by tandem mass spectrometry (MS/MS) are compared with previously identified reference spectra (Craig, Cortens, and Beavis 2005). The benefits to library searching as opposed to database searching, in which spectra are compared with spectra predicted from amino acid sequences (Eng, McCormack, and Yates 1994), is a more accurate comparison of fragment ion intensities and a more efficient spectra search.

The Skyline ecosystem includes a suite of software tools, Bibliospec (Frewen et al. 2006), for creating and searching MS/MS peptide spectrum libraries. The Bibliospec 2.0 software package is composed of two informatics tools: BlibBuild and BlibFilter. All Skyline installations include these tools, and Skyline itself provides user interface for creating spectral libraries. The first step in building a spectral library is creating a full redundant library of peptide MS/MS spectra matched with known peptide identifications, which is performed computationally by BlibBuild and written to sqlite3 database file. To obtain peptide identifications for this step, an assortment of available database search programs are supported by BiblioSpec 2.0 (Table 2). Second, BlibFilter refines the redundant library to choose just one representative spectrum for each peptide, preserving the original retention times of the redundant spectra, and then writes a new non-redundant sqlite3 database containing this information. BlibFilter chooses the one representative spectrum by measuring

the similarity between all pairs of redundant spectra for a given peptide, and selecting the spectrum with the highest average similarity score.

The Skyline GUI also supports MS/MS spectral library creation. To do so, it takes the best scoring PSM from a variety of supported search engines (Table 2) as a reference spectrum, picking the most intense in the event of a tie. In addition to creation of spectral libraries, Skyline supports several sources of reference libraries, including Peptide Atlas (Desiere et al. 2006), the National Institute of Standards and Technology (NIST), and the Global Proteome Machine (GPM) (Craig, Cortens, and Beavis 2004). Most Skyline users will choose to use their spectral libraries, once created, for targeted method creation and data extraction.

E. Skyline for small molecule research

Although this review is focused on the Skyline ecosystem for quantitative proteomics, the ecosystem also works for generalized small molecules (Tang et al. 2015), such as lipidomics, glycomics, and metabolomics. While some functions do not yet work for non-proteomic data, online tutorials detailing with how to make use of the Skyline ecosystem for small molecule research, including assay development, are available on-line with the Skyline software documentation.

Generally, the Skyline informatics for small molecule assay development mirrors that proteomic experiments described above. A notable difference, however, is the way Skyline treats ionization. For proteomics data, typically only sequence and charge state are required to describe a charged peptide. As such, Skyline assumes ionization by protonation, the most typical ionization for these experiments. Ionization of small molecules occurs through many means, including sodium addition and hydrogen loss. Therefore, Skyline's informatics work best with manually entered charges states and either generalized ion formulas or manually entered m/z values for precursors and products.

F. Isolation window determination for DIA experiments

Unlike targeted experiments, DIA experiments do not require selection of proteins, peptides, or transitions prior to acquisition. There are multiple data collection strategies for DIA experiments with associated advantages and disadvantages that have been evaluated elsewhere (Chapman, Goodlett, and Masselon 2014). The most basic method used with Skyline (Egertson et al. 2015) acquires MS and MS/MS data for all molecular species between a certain predefined precursor m/z range in specified fragment m/z isolation windows. Determining the most appropriate MS/MS isolation scheme requires consideration of the particular instrument's scan rate, resolving power, dynamic range, and sensitivity of the mass analyzer (Zhang et al. 2015). For many DIA experiments analyzed with Skyline, our lab monitors a precursor m/z range of 500–900 m/z as this m/z range reflects most proteotypic peptides. Restricting the total range can allow for smaller, more selective precursor isolation windows or shorter cycle times. Skyline is extremely flexible and currently supports all commonly used isolation schemes.

For the precursor m/z isolation scheme, window placement is calculated one of two ways: integer or optimized. Simple arithmetic division is used for integer window placement. For

example, a 20 window isolation scheme with each window covering 5 m/z (20×5) for a 500–600 m/z range are placed at 500–505 m/z, 505–510 m/z, etc. This method requires a margin (usually 0.5 m/z) added to the instrument method but ignored during extraction, e.g. 499.5–505.5 m/z, 504.5–510.5 m/z, etc. Alternatively, optimized window placement considers peptide mass distribution and calculates isolation windows that encompass “allowable regions” (Egertson et al. 2013). By placing window edges at “forbidden zones” where peptide masses do not occur and windows over “allowable regions”, the resulting window width and position is optimized for m/z ranges where peptides are most likely occur. This algorithm for calculating optimized isolation window placement is integrated into Skyline, facilitating quick generation of isolation lists for DIA methods.

G. Final method export and refinement

Once a Skyline document is built with the settings and optimizations described above, the final developed assay is exported either as a native method for triple quadrupole instruments or as scheduled isolation lists for certain Q-TOF and the Thermo Q-Exactive instruments. After acquiring mass spectrometry data, the acquisition files are imported into the Skyline document for method refinement such as peptide and transition validation. The cycle of export, acquisition, and refinement is repeated until the assay is considered effective, at which point final acquisition and quantitative analysis begins.

III. Data processing: Peak detection and integration

Skyline’s targeted data analysis strategy begins when the researcher selects raw mass spectrometer acquisition files to import. Skyline derives information from the native, vendor-specific file formats or from portable files like mzXML (Pedrioli et al. 2004) or mzML and caches the information into a single, high-performance data file. The caching step is critical to Skyline’s ability to quickly load large experiments with many data files, allowing researchers to process multiple MS runs at the same time. Skyline handles files sequentially or in parallel, performing the operations described below on each data file. The end result of Skyline’s data processing is a calculated peak area, or area under the curve (AUC), for each peptide ion (modified peptide plus charge state) in the Skyline Target list, visualizations of the data, and cached chromatogram information for quick recall.

A. Chromatogram extraction

Mass spectrometry data contains three dimensions: m/z, retention time, and intensity. In the first step of data processing, Skyline extracts the retention time and intensity information for a given m/z (Figure 2, Step 1). For PRM or DIA experiments, this information is calculated from the measured spectra as extracted-ion chromatograms (XIC), and for SRM/MRM experiments, the measured chromatograms are themselves imported. No file conversion is necessary prior to this step; raw files from the instrument are directly imported. It should be noted, however, that several settings in Skyline affect the chromatogram extraction process, such as retention time window width and parameters for instrument resolving power for profile spectra or mass accuracy for centroided spectra, therefore researchers should be sure that the Skyline document is prepared with the appropriate instrument and experimental details before importing data. These settings can be exported and imported from other

Skyline documents, aiding repeatability in data processing and ensuring the proper instrument and experimental details are preserved across laboratory sites and experiments.

B. Resampling

For all tandem mass spectrometry data acquisition types, the time intervals between MS2 scans are irregular. For example, in an SRM/MRM experiment, the rate of MS2 scans depends on the number of transitions scheduled for collection at a given time and the dwell time for each. For its purposes, Skyline requires all chromatogram time, intensity points for a peptide to be placed on a uniform scale with a consistent interval. Even for DIA, this requires some adjustment of MS1 with MS2 scans and ions for multiple charge states or isotope labeling. To place these points, a linear interpolation of each raw chromatogram is performed. Skyline calculates an interval that captures as much information about the peak as possible (Figure 2, Step 3). Intervals placed too wide distort the shape of the peak, while intervals too narrow are costly in storage and processing time. The end product of resampling is an interval width that works best for the dataset, avoiding as much distortion as possible.

C. Peak detection

The resampled data is then searched for areas that represent peaks. Peak detection is performed by the Chromatogram Retention time Alignment and Warping for Differential Analysis of Data (CRAWDAD) Peaks algorithm. (Finney et al. 2008, Finney 2012) CRAWDAD finds the maxima and minima by points where the first derivative is equal to zero, then takes the second derivative in the retention time dimension, noting the point at which the second derivative is equal to zero in order to find inflection points. This set of points (local maxima, local minima, and inflection points) define a detected peak. In the absence of spectral library retention time information for peptide spectrum matches (IDs) within the files being analyzed (usually for DDA, PRM or DIA - with initial processing by tools like DIA-Umpire (Tsou et al 2015)), Skyline takes only the 20 most intense peaks for each transition from CRAWDAD. When ID times are present, Skyline also includes all CRAWDAD detected peaks containing IDs, or aligned IDs in runs which do not contain any IDs for the target being analyzed. This results in an initial set of raw peak detections for each individual chromatogram with boundaries set at the inflection points and peak areas in interval units.

D. Peak grouping

Next skyline creates peak groups for each targeted modified peptide or molecular structure, combining the raw peaks for its chromatograms and grouping them by retention time overlap. Peak grouping is based on elution profile similarity (Figure 2, Step 4), with apex RT, start RT, and end RT drawn from the local maxima and inflection points from the previous step. It should be noted that different charge states and isotopes (heavy labeled peptides, medium labeled peptides, endogenous or light peptides) are each considered together. After grouping, the individual peak boundaries are replaced with a single boundary for each entire peak group. This boundary may be adjusted outward from the original 2D inflection point boundary, using Savitzky-Golay smoothing and combined information of all chromatograms contributing to the peak group. Peak statistics are also recalculated to reflect

the new agreed-upon boundary values and interval unit areas are multiplied by the number of seconds in the chosen interval to yield an ion count estimate (ions/second * seconds = ions).

E. Peptide identification

During the peptide identification step, commonly called “peak picking”, the top 10 results from peak grouping are evaluated for probability that they represent the peptide. For each of the 10 considered peak groups, a number of peak group features are calculated. These features, derived both from the CRAWDAD calculate statistics and raw chromatogram data, are weighted with particular coefficients, and summed to give a final score to the peak group. The seven scores and corresponding coefficients in Skyline’s default peak picking model are log intensity (1.0), coelution count (1.0), identified count (20.0), library intensity correlation (3.0), shape score (4.0), weighted co-elution (−0.05), and retention time delta from prediction (−0.7). The peak group with the highest score is identified (“picked”) as the peak for that peptide.

Many of these scoring features used in the Skyline default peak picking strategy are similar to those used in the mProphet method (Reiter et al. 2011). Researchers also have the ability to use other peak picking algorithms, such as the mProphet model itself, after initial data import by using a Re-integrate command to generate and apply these models, using decoys and semi-supervised machine learning. As evident from the exceptionally high weight given to the identification count feature, if external tools for peptide identification are used to identify a time of peptide elution within the data, Skyline will give very high priority to finding a peak at that time, using retention time alignment between runs to propagate ID times between runs.

F. Peak area calculation

In Skyline, the peak area, or area under the curve (AUC), refers to the total integrated area within the peak boundaries, minus the background area (in intensity for seconds of time units - or ion count where intensity is ions per second). Background area is defined as the total integrated area of the minimum of background height and intensity at each point, where background height is the minimum intensity of the two points where the chromatogram crosses the integration boundaries, which is assumed to be the level of intensity contributed not by the transitions themselves but from chemical noise (background) in the measurement. The background area is subtracted from the total integrated area within the peak boundaries to return the final reported peak area. Although Skyline allows display of chromatograms with various smoothing options (2D, 1D, Savitzky-Golay) applied, it uses the interpolated points displayed in the unsmoothed graphs to calculate peak area. Total area values sum the AUC values of individual chromatograms, rather than performing a separate AUC calculation on a summed chromatogram.

IV. Core analyses and visualizations

Once raw acquisitions are processed, Skyline creates visual displays of the data. Chromatograms for each peptide in the Skyline document are displayed with visualizations of the boundaries and indicators for the retention time and dot product of each picked peak.

Retention times for the top 10 peaks detected in the RT window are also shown, allowing researchers to see other candidates that were considered in peak picking.

A. Data curation and quality assessment

Visualizations in Skyline allow researchers to quickly identify issues in data, explore causes, and evaluate solutions to resolve the issues. One common example of this functionality of data visualization in Skyline is “peak picking”. Although automated peak detection and boundary setting are generally reliable, it is important to manually curate data to ensure reliable quantification (Bereman et al. 2012). Here, Skyline’s visualizations facilitate determination of which peptides can be robustly measured in a specific target matrix, which transitions for a peptide are the best transitions for the measurable peptides, and whether a given peak actually measures the peptide of interest. The picked peak is marked by a solid black arrowhead in Skyline’s chromatogram window (Figure 3a). Evaluation of peptide identification (“peak picking”) is computationally-aided by display of iRT-predicted RT, relative transition intensities compared to library intensities. Dot product values are calculated (Stein and Scott 1994; Tabb et al. 2003), correlating peak intensities of the transitions with the library spectrum for that peptide (dotp - and between precursor isotope peak intensities and expected isotope distribution - idotp - and between analyte peak intensities and those for matching isotope labeled reference peptides - rdotp) and establishing a measure of confidence in peak detection (Prakash et al. 2009; Sherwood et al. 2010). Peak boundaries are also displayed as dashed vertical lines, shown in Figure 3a, and researchers are able to adjust the boundaries as they deem appropriate. Skyline recalculates peak statistics, including peak area integration, with the new boundaries or peak picking.

Critically for quantification, Skyline allows convenient evaluation of transitions. Skyline gives the option to display for each peptide all transitions included in the document, precursors-only (M, M+1, M+2, etc.), products-only, a single transition, or a total ion chromatogram, summing all transitions, for each precursor. The individual fragments measured for a peptide are visualized as different colored chromatograms (Figure 3a). The ability to simply delete or add transitions for a peptide precursor in the Target window, and easily undo such changes, lets researchers visually evaluate transitions for characteristics such as intensity, co-elution with interference, shouldering, and other qualities undesirable for accurate, robust quantification. For MRM experiments with heavy-paired peptide targets, the Automated Detection of Inaccurate and Imprecise Transitions in Peptide Quantification (AuDIT) algorithm (Abbatiello et al. 2010) employed by the Skyline External Tool QuaSAR automatically suggests transitions for removal based on similar criteria. In addition to the chromatogram view, clicking on a chromatogram opens a Full-Scan view of normal 2D spectra (intensity by m/z).

B. Native, real-time updating visualizations

Statistics for data are shown as visual graphs in embeddable live plot windows. Statistics include plots of retention time, peak area, mass error, and group comparisons. The retention time display is user-defined to show a floating column chart by replicate or peptide, a linear regression plot of the peptide elution times by SSRCalc or iRT score, or a scheduling window with the number of expected transitions over time for multiple scheduling window

widths. Retention time data can be plotted by Replicate Comparison or Peptide Comparison, allowing researchers to evaluate various aspects of their data. Specifically, replicate comparisons can be sorted as they are in the document or by acquired time helping to make the impact of instrument run order more easily understood. For example, when the retention times are displayed as Replicate Comparison for an experiment, it is clear if a particular run deviates significantly from others (Figure 3c), which may indicate a potentially mis-picked peak. Options for display of peak areas allow the researcher to specify between displaying a bar chart of total peak areas, peak areas normalized to heavy peptide isotope pairs, user-specified global standards (Figure 3d), maximums, or the total peak area; or to view bar graphs of coefficient of variance (CV) (Figure 3b). Similar to notably deviating retention time values, an outlying peak area may prompt a researcher to visually examine that replicate or peptide.

In addition to retention time and peak area data, mass error graphs are available for inspecting mass error summary information. Mass error is calculated in Skyline as a weighted mean of the mass error in all the integrated points across the annotated chromatogram. When visualized as a Replicate Comparison, this data is helpful for detecting interference at the transition level. As a Peptide Comparison, researchers may sort by mass error to get an overview of all targeted peptides. Unique to the mass error visualization options are a histogram (for display of mass error at the full document scope or each replicate for detecting calibration issues and a 2D histogram with m/z and retention time dimensions available for increased visibility of instrument calibration issues.

For instances where displaying data in the form of Replicate or Peptide Comparison is inadequate, Skyline offers options for grouping and ordering of peptides by a number of characteristics, including custom annotations that researchers can add based on experimental details or sample characteristics. The Group Comparisons feature natively calculates differential statistics for proteins in a table or graph view within Skyline. For many proteomics studies, correcting for multiple hypothesis testing is required. To calculate statistically significant differential expression, Group Comparisons employs a user-specified cut-off for the Benjamini-Hochberg adjusted p-value to account for false discovery rate (Benjamini and Hochberg 1995).

In experiments where absolute quantification of the analyte target is necessary, Skyline allows for internal single point calibration to a reference and also multiple point calibration curves via the Calibration Curve feature. The Calibration Curve feature works with data from a dilution series of isotope-labeled reference peptides. This external calibration curve is used to regress the known concentration of each reference peptide target against the intensity measured for that target, allowing conversion of intensity measurements into absolute quantitative values. Although this method requires multiple injections to gather the external calibration curve data, the Calibration Curve feature accounts for linear peptide responses that have nonstandard slopes or intercepts. At this time, the feature provides conversion of measured intensity values to absolute quantitation values like concentration, not for determining limits of detection or limits of quantitation.

C. Skyline informatics considerations for ion mobility spectrometry

In experiments involving gas-phase ion mobility spectrometry (IMS) separations in place of or hyphenated with LC, the additional dimension of drift-time is introduced to the data (Baker et al. 2015). For these datasets, as a single LC RT has multiple associated drift-times, Skyline considers drift-time data in processing, allowing chromatogram extraction to be limited to specified drift time ranges, and visualization. Spectra from which chromatogram points are extracted can be visualized in a 3D heat map plot (intensity by m/z and drift time), displayed when the chromatogram is clicked on. As fragments have the same drift-time as their precursor (potentially slightly offset by a constant fragmentation factor) a drift time value and extraction range allow Skyline to ignore signal outside a targeted drift range, improving selectivity. Skyline's incorporation of IMS considerations and continuing optimization of IMS informatics holds promise for analysis of large, multi-dimensional datasets involving IMS.

V. Additional analyses: external tools

A. Goals for External Tools

One distinguishing aspect of the Skyline ecosystem is the ability for researchers to contribute their data processing software packages through the external tools framework (Broudy et al. 2014). Through this framework, researchers can conveniently and quickly distribute their programs to the community. The ultimate goal is to provide a common, convenient hub that connects the data found in a Skyline document with the community's many informatics methods. Although Skyline itself is built from the C# programming language, the installable tools framework includes extra support for tools using the R or Python programming languages. To date, nine external tools from community researchers are integrated in the Skyline ecosystem with applications ranging from assay development to biological inference (Table 3).

B. External tools for assay development

Generating a specific hypothesis for a quantitative MS experiment often begins with prior knowledge from previous proteomics experiments. The Biodiversity Library Plugin (Payne et al. 2015) enables fast, convenient survey and retrieval of existing proteomics data for an organism and biological pathway of interest. Researchers can query spectra for over 3 million peptides and 230,000 proteins, annotated with KEGG pathways, from 118 organisms. These functionalities allow researchers to quickly compile a list of potential assay proteins on the basis of a biological function.

As mentioned in the computationally-assisted assay development section, selecting target peptides for an SRM/MRM or PRM poses a significant challenge. One such challenge in clinical applications is natural genetic variation, which may confound MS experiments that attempt to measure a specific protein. The Population Variation external tool (Fujimoto et al. 2014) enables researchers to explore possible variants for their protein of interest by surveying the dbSNP and 1000 Genome project for mutations. The PREGO external tool (Searle et al. 2015) is an algorithm that ranks peptides by their predicted response level, intended to facilitate the selection of peptides that will produce the most intense MS signal.

C. External tools for acquisition monitoring

It is necessary to control for LC-MS performance variations during acquisition in order to ensure accurate, reproducible measurements. Aspects such as retention time, chromatographic peak width, mass measurement, and ion intensity all influence the robustness of an assay and are affected run to run by minor, necessary adjustments like column changing. The external tool Statistical Process Control in Proteomics (SProCoP) (Bereman et al. 2014) allows for semi-automated real time evaluation of an assay, including both chromatographic and mass spectrometric performance. SProCop assesses metrics such as retention time reproducibility, peak asymmetry, targeted peptide ion intensity, and mass measurement accuracy, constructing control charts and boxplots that a researcher monitors throughout the lifetime of an experiment to ensure reproducibility between LC-MS runs.

D. External tools for quantitative statistical analysis

The experimental workflow used to generate samples for mass spectrometry each require specialized data analysis strategies. The combination of sample generation method (labeled versus label-free) and the spectral acquisition method (DDA, SRM/MRM and PRM, or DIA) require different informatics approaches. The external tool MSstats (Choi et al. 2014) considers these data properties to calculate the relative quantification of proteins and peptides. MSstats begins with data processing and visualization of the identified and quantified spectral peaks. It then performs statistical modeling and inference using linear mixed models, customized to the method of sample generation and MS acquisition. Finally, researchers can specify a particular statistical power for their experiment, and MSstats determines the minimal number of replicates required to achieve that statistical power by considering the dataset as a pilot experiment.

Other external tools are designed for use with specific acquisition methods. For DDA analyses, an MS1 filtering approach through the external tool MS1Probe (Schilling et al. 2012) enables high throughput statistical quantification of peptide analytes. The external tool QuaSAR (Mani, Abbatiello, and Carr 2012) produces figures of merit (limit of detection, LOD; limit of quantitation, LOQ) for statistical characterization of stable isotope dilution MRM-MS assays (SID-MRM-MS) generated with heavy labeled stable-isotope peptide standards. Within the QuaSAR external tool, AuDIT (Abbatiello et al. 2010) performs automated filtering of transition validation, improving sensitivity and specificity for peptide quantitation by SID-MRM-MS. For label-free quantitative DIA analyses, Skyline exported custom reports can be used to optimize fragment selection and detect interferences using the nonoutlier fragment ion (NOFI) ranking algorithm (Bilbao et al 2015).

In addition to the tools described above, Skyline also enables the export of results for analysis in other software suites. The MPPReport tool, for example, creates a results file designed for import into Agilent's Mass Profiler Professional multivariate statistics software package. Researchers can create their own custom reports with a wide range of values to view, edit, and export. Exported custom reports enable researchers to perform their own statistical analyses in Excel, R, Matlab, Java, C++, and other languages, and formats of custom reports can be saved as templates to share and re-use in future analyses.

E. External tools for biological inference

The ultimate goal of many MS proteomics experiments is deriving biological information. Towards this end, researchers have developed several tools to facilitate the visualization and biological importance of peptide and protein measurements. The external tool Protter (Omasits et al. 2014) combines known annotations of protein structure and function with experimental MS data to give researchers an interactive visualization of protein topology. Protter is especially powerful for visualization of membrane protein topology.

VI. Methods and results sharing

Skyline, being designed for the mass spectrometry proteomics community, is ideal for interlaboratory collaborations and experimental results comparisons in a vendor-neutral manner. With these types of collaborations in mind, the Skyline ecosystem grew to include storage and sharing applications.

A. Panorama and CHORUS projects for raw and Skyline file storage and sharing

Panorama (Sharma et al. 2014), a web-based application for storing, sharing, analyzing and reusing targeted Skyline assays, allows laboratories to communicate the details for replicating or reproducing targeted Skyline experiments. To this end, during the development of Panorama, data integrity, security, and scalability were stressed. Storing Skyline documents in Panorama does not confer any loss of information and data can be made public or kept private at the discretion of the researcher.

It is possible to automate entire informatics pipelines, from acquisition to Panorama publishing, using the command-line version of Skyline, called SkylineRunner. An exemplary case of informatics automation is AutoQC, a completely automated pipeline designed to monitor system suitability in bottom-up proteomics (Bereman et al 2016). As a mass spectrometer runs, AutoQC imports quality control acquisitions into Skyline, extracts multiple identification-free metrics, and uploads the data to a Panorama Skyline document repository. Users can view system suitability metrics in the web-based interface, including Levey-Jennings and Pareto plots.

In addition to the Panorama module, the CHORUS platform was developed to provide storage, analysis, and sharing function for raw mass spectrometry files with a simple user interface. When raw data is placed into CHORUS, it is uploaded to the Amazon Web Services (AWS) cloud and translated into a distributed data structure. By utilizing AWS cloud computing and the unique distributed file format, accessing DIA data remotely from CHORUS is faster than from the local hard drive. When researchers wish to request data from the cloud, Skyline requests the extracted ion chromatograms, CHORUS generates the chromatograms, and then returns a Skyline cache. In addition to this scalable data access and remote extraction of chromatograms, CHORUS also provides a browser-based vendor-neutral spectrum and chromatogram viewer, integrated protein database searching and quantitative analysis tools. CHORUS is intended to facilitate community-driven mass spectrometry proteomics, and is therefore a not-for-profit public/private partnership.

B. CPTAC: an exemplary use case scenario

The Clinical Proteomic Technologies Assessment for Cancer (CPTAC) program (Abbatiello et al. 2015) exemplifies the strengths of Skyline for methods and results sharing in large, multi-site collaborations. As part of the CPTAC efforts to improve cancer diagnosis, treatment, and prevention with LC-MRM-MS methodologies, the Skyline ecosystem has been utilized to develop targeted proteomics assays that are precise, accurate, reproducible, and transferable between laboratories, across expertise levels, and over instrument platforms. CPTAC scientists utilized the Skyline ecosystem for computationally-assisted methods development, taking ease of simple transition evaluation, retention time scheduling, and method export. Additionally, because Skyline's analysis pipeline is instrument-independent, the CPTAC researchers were able to integrate data across LC-MS platforms. Further, informatics tools developed by the CPTAC team to quantitatively analyze the data, namely QuaSAR, have been integrated into the Skyline ecosystem as external tools. From assay development to quantitative data analysis, the Skyline ecosystem helped to enable scientists of the CPTAC consortium accomplish their goals for a robust, sensitive absolute quantification assay across laboratory sites, instrument platforms, and operators.

VII. Perspectives

The Skyline informatics ecosystem described above has become a powerful tool in the quantitative measurement and analysis of peptides by mass spectrometry. Skyline's generalized, vendor-neutral design provides the base for an informatics toolkit that expands to fit the needs of the community. As new needs arise from the community, Skyline frequently releases software developments in the form updates for Skyline-daily, the beta release version of Skyline. Areas of orthogonal interest such as small molecule research, analytical methods for rigorous quantitation, and statistical techniques are inspiring new Skyline developments. Important future goals are adapting Skyline's informatics for big data mass spectrometry proteomics through parallelization of file processing. These developments will be vital in obtaining the robust, sensitive quantitative measurements required to better understand the systems biology of cells, organisms, and disease states.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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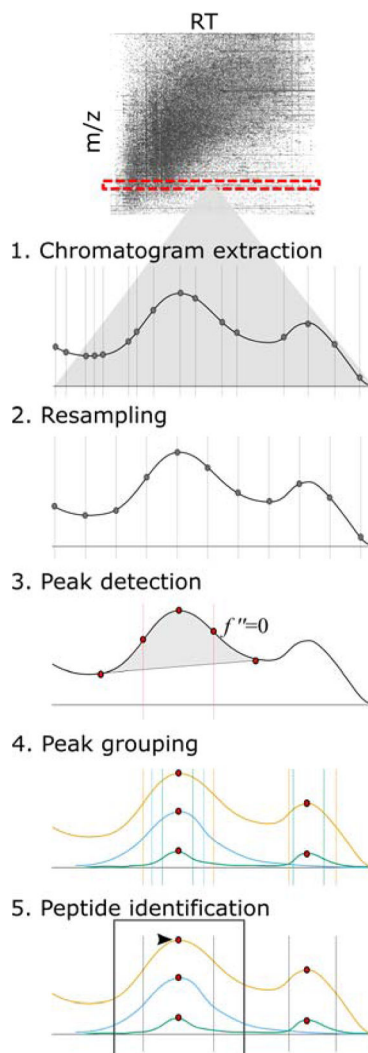


Figure 1. Generalized workflow for quantitative MS assay development

Six main steps are outlined, beginning with the development of a hypothesis and continuing through additional analyses, with examples of the associated Skyline ecosystem features.

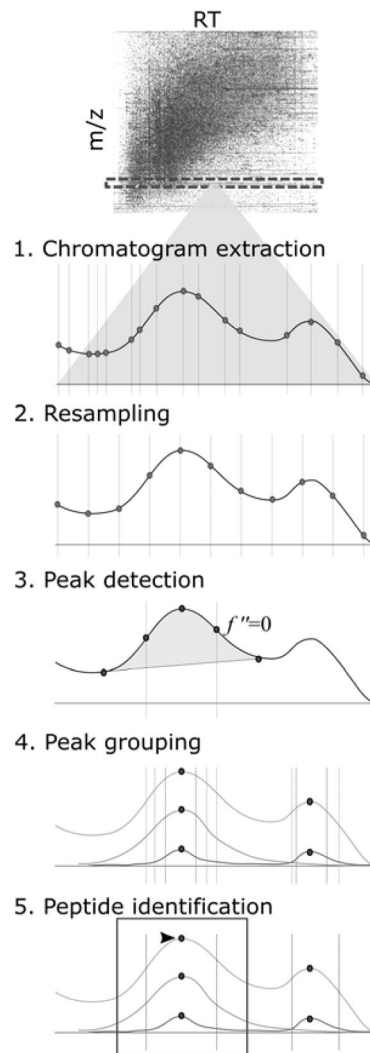


Figure 2. Data processing pipeline in Skyline

Skyline derives information from native, vendor-specific file formats or from portable files, producing peak area calculations, and visualizations of the data.

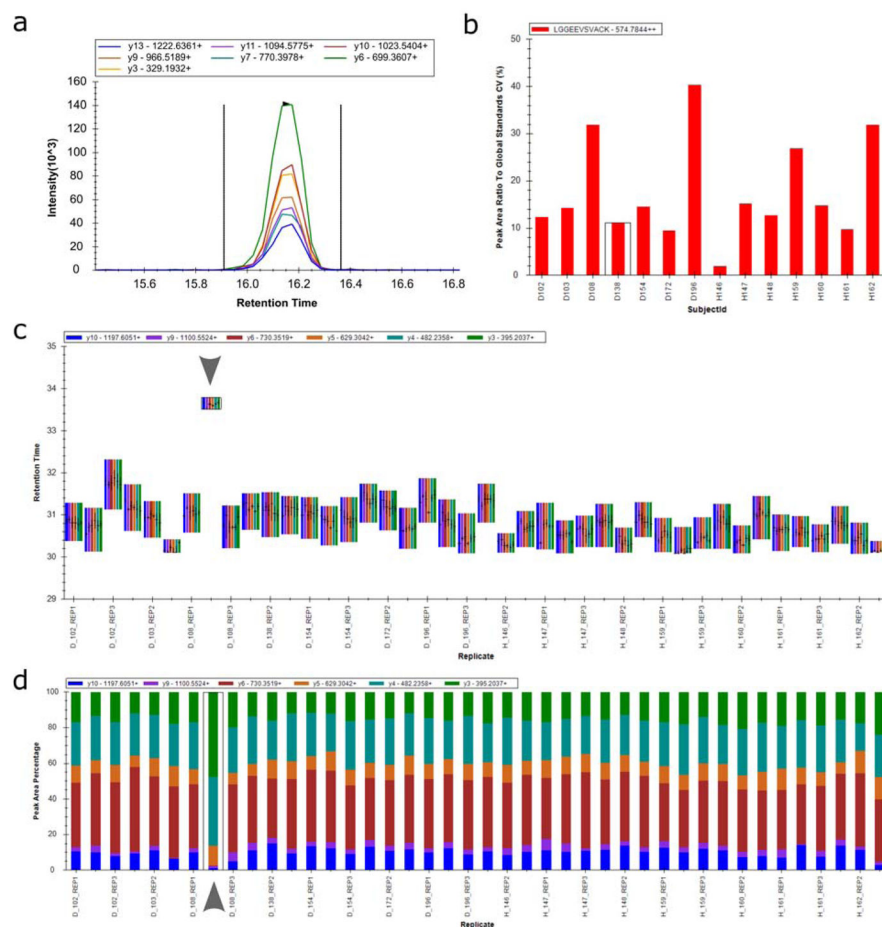


Figure 3. Real-time updating visualizations natively embedded in Skyline

(a) Skyline chromatogram visualizations show the intensity at each resampled retention time point for all fragment ions (displayed as different colored lines identified in the legend) of a precursor, enabling researchers to assess Skyline's automated peak picking or adjust integration boundaries if necessary. (b) Calculation of coefficient of variation (CV) informs researchers of the reproducibility of peptide peak areas (shown here as the peak area ratio to a global standard) over multiple acquisitions or custom-annotated groups of acquisitions. (c) Real-time updating visualization of precursor retention time across acquisitions enables quick identification of mis-picked peaks over many MS acquisition runs. Out of 42 replicates, the peptide shown here appears to elute three minutes late in one replicate (eighth from the left, marked with arrow) compared to all other replicates, an observation that may prompt the researcher to evaluate that picked peak in the chromatogram visualization pane. (d) Peak area is displayed here as the percentage contributed by each fragment ion of the precursor which allows the researcher to quickly evaluate data quality. For example, the boxed replicate (eighth run from the left, marked with arrow) displays a noticeably different distribution of contributed fragment peak areas, indicating that the picked peak group for this replicate may require further examination.

Table 1
Proprietary file formats supported by Skyline

Vendors and instruments supported by the Skyline ecosystem are specified along with their respective proprietary file format and general acquisition types. (QqQ: triple quadrupole; Q-TOF: quadrupole time of flight; IMS-TOF: ion mobility spectrometry-time of flight; Q-OT: quadrupole-Orbitrap; Q-LIT: quadrupole-linear ion trap)

Vendor	File extension	Instruments Supported	Acquisitions Supported
Agilent	.d (directory)	QqQ, Q-TOF, IMS-TOF	DDA, SRM, DIA
Bruker	.d (directory)	Q-TOF	DDA, PRM, DIA
Sciex	.wiff (file)	QqQ, Q-TOF	DDA, SRM, PRM, DIA
Shimadzu	.qgd	QqQ	SRM
Thermo	.raw (file)	QqQ, Q-OT, Q-LIT	DDA, SRM, PRM, DIA
Waters	.raw (directory)	QqQ, Q-TOF, IMS-TOF	SRM, PRM, DIA

Table 2

Peptide spectrum matching pipelines supported by Skyline with BiblioSpec for spectral library-building.

Peptide spectrum matching pipeline	Type	Creator	Peptide ID file	Spectrum file
Mascot	Proprietary	Matrix Science (Perkins et al 1999)	.dat	
ByOnic	Proprietary	Protein Metrics, Inc. (Bern, Cai, and Goldberg 2007)	.mzid	.MGF, .mzXML, .mzML
Comet/SEQUEST/Percolator	Open source	Dept Genome Sciences, University of Washington (Eng, Jahan, and Hoopmann 2013; Eng, McCormack, and Yates 1994; Kall et al 2007)	.perc.xml (.sqt)	.cms2, .ms2
ID Picker (Myrimatch)	Open source	MSRC Bioinformatics, Vanderbilt University (Tabb, Fernando, and Chambers 2007)	.idpXML	.mzXML, .mzML
MaxQuant Andromeda	freeware	Max Planck Institute (Cox et al 2011)	msms.txt	
Morpheus	Open source	Coon lab, University of Wisconsin-Madison (Wenger and Coon 2013)	.pep.xml, .pep.XML, .pepXML	.mzXML, .mzML
MS-GF+	freeware	Pevzner lab, UCSD (Kim et al 2010)	.mzid, .pepXML	.MGF, .mzXML, .mzML
OMSSA	Open source	NCBI (Geer et al 2004)	.pep.xml, .pep.XML, .pepXML	.mzXML, .mzML
PEAKS DB	Proprietary	Bioinformatics Solutions, Inc. (Zhang et al 2012)	.pep.xml, .pep.XML, .pepXML	.mzXML, .mzML
Proteomics Identifications (PRIDE)		EMBL-EBI (Martens et al 2005)	.pride.xml	
Protein Pilot	Proprietary	SCIEX (Shilov et al 2007)	.group.xml	
Protein Prospector	Open source	UCSF Mass Spectrometry Facility (Baker and Clauser)	pepXML/mzXML	
Proteome Discoverer	Proprietary	Thermo	.msf	
Scaffold	Proprietary	Proteome Software (Searle 2010)	.mzid	.MGF, .mzXML, .mzML
Spectrum Mill	Proprietary	Agilent	.pep.xml, .pep.XML, .pepXML	.mzXML, .mzML
Trans-Proteomic Pipeline (TPP)	Open source	Aebersold lab, Institute for Systems Biology (Deutsch et al 2015)	pepXML/mzXML	
X! Tandem	Open source	Global Proteome Machine Organization (Craig and Beavis 2004)	.xtan.xml	
ProteinLynx Global SERVER (PLGS) - MS^e	Proprietary	Waters	final_fragment.csv	

Peptide spectrum matching pipeline	Type	Creator	Peptide ID file	Spectrum file
Custom			.ssl	

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Table 3

Community-built informatics tools integrated into the Skyline ecosystem.

Tool	Creator	Integration Date	Purpose
BiodiversityPlugin	Computational Proteomics Group, Pacific Northwest National Laboratory (Payne et al 2015)	2015 Jun 10	mass spectrometry data retrieval by organism and biological pathway
MPPReport	Agilent Technologies	2014 Sep 9	data export for use in Agilent's Mass Profiler Professional multivariate statistics software
MS1Probe	Gibson Lab, The Buck Institute for Research on Aging (Schilling et al 2012)	2014 Apr 16	high throughput statistical quantification of MS1 Filtering datasets
MSstats	Vitek Lab, Purdue University (Choi et al 2014)	2015 Jul 30	statistical relative quantification of proteins and peptides in global, targeted, and data-independent proteomics
Population Variation	Computational Proteomics Group, Pacific Northwest National Laboratory (Fujimoto et al 2014)	2013 Dec 20	protein variant lookup from dbSNP and the 1000 Genome project
Prego	MacCoss lab, University of Washington (Searle et al 2015)	2015 Jun 23	peptide SRM response prediction
Protter	Wollscheid Lab, ETH Zurich (Omasits et al 2014)	2015 Dec 19	transmembrane protein topology visualization
QuaSAR	Carr Lab, Broad Institute of MIT and Harvard (Mani, Abbatiello, and Carr 2012)	2014 Oct 23	QC, statistical analysis, and visualization of data from quantitative MRM-MS
SProCoP	Bereman Lab, North Carolina State University (Bereman et al 2014)	2014 Dec 3	Visualization, detection, and identification of assignable causes of variation in LC-MS