Protein biocargo of citrus fruit juice sac cells-derived vesicles reveals heterogeneous transport and extracellular vesicle subpopulations

Running Title: Protein cargo of citrus fruit vesicles

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Abstract

Cellular vesicles are membrane-enclosed organelles that transport material inside and outside the cell. Plant-derived vesicles are receiving more and more attention due to their potential as nanovectors for the delivery of biologically active substances. We aimed to expand our understanding about the heterogeneity and the protein biocargo of citrus fruit juice sac cell-derived vesicles. Micro- and nano-sized vesicle fractions were isolated from four citrus species, *C. sinensis*, *C. limon*, *C. paradisi* and *C. aurantium*, characterized using physicochemical methods and protein cargos were compared using label-free quantitative shotgun proteomics. In each sample approximately 600-800 proteins were identified. Orthologues of most of the top-ranking proteins have previously been reported in extracellular vesicles of mammalian origin. High expression of patellin-3-like, clathrin heavy chain, HSPs, 14-3-3 protein, glyceraldehyde-3-phosphate dehydrogenase and fructose-bisphosphate aldolase 6 could be observed in all the vesicle samples while Aquaporin was highly expressed only in nanovesicles. Bioinformatics revealed more than hundred protein orthologues potentially implicated in vesicular trafficking. In particular, the presence of CCV, COPI and COPII coat proteins indicates the presence of highly heterogeneous populations of intracellular transport vesicles. Moreover, the differential expressions of hydrolases and oxidoreductases enabled us to gain insights into their functions in citrus fruit sac cells.

Keywords

nanovectors, citrus, fruit juice sac cell, vesicles, extracellular vesicles, vesicular trafficking, proteomics, enzymes, oxidoreductases, hydrolases, bioinformatics

1. Introduction

Cellular vesicles are fluid filled lipid bilayer enclosed organelles within or outside the plasma membrane (PM) used to transport materials. Formation and secretion of vesicles are evolutionary conserved and hence vesicles are ubiquitous in all three primary kingdoms, bacteria, archaea and eukaryotes. Vesicles can be classified based on their size, function, location and the nature of their cargo. In plant cells principally four types of vesicles can be distinguished: the large central vacuole [1], transport vesicles [2], secretory vesicles [3] and apoplastic vesicles [4]. The vacuole, transport and secretory vesicles are found intracellularly while apoplastic vesicles are extracellular. Plant vacuole plays an important role in molecular storage, degradation and maintenance of turgor pressure. Transport vesicles are involved in the exchange of lipids, nucleic acids, proteins and small soluble molecules between cellular organelles and compartments within the cytoplasm. For instance, from the Golgi to the endoplasmic reticulum (ER) and from the Golgi to the PM along the biosynthetic-secretory pathway, or from the PM to the vacuole through the endosome through the endocytic pathway. Interestingly, vacuole intrinsic vesicular transport [1] and transport vesicles in other organelles like chloroplasts [5] and mitochondria [6] have also been observed. Besides structural and functional similarities with mammalian and yeast vesicles and vesicle mediated trafficking, plant cells show considerable differences too. One of the peculiarities, for instance, is the mobile secretory vesicles cluster (SVC) that carry cargo molecules to the extracellular space through the PM and cell plate [7]. Moreover, the existence of COPII transport vesicles in highly vacuolated plant cells is argued along with the mechanism that drive membrane trafficking between the ER and the Golgi apparatus [8]. In plants, the existence, secretion and role of extracellular vesicle (EVs) are much less understood that those of mammalian cells and biological fluids which are well characterized [4, 9, 10]. In fact, there are only few studies reporting characterization of EVs isolated from the extracellular apoplastic fluids of Arabidopsis leaf [4] and sunflower seeds [11].

Recently, nanometer-sized membrane vesicles have been isolated from complex matrixes, such as homogenized roots of ginger and carrot [12] and the fruit juices of grape [13], grapefruit [14], and lemon [15] using the gradient ultracentrifugation (UC) method commonly used for the isolation of mammalian EVs. It has been shown by physiochemical methods (like electron microscopy, EM and dynamic light scattering, DLS) and by molecular characterization (proteins, lipids and RNAs cargo)

that plant-derived nanoparticles are indeed vesicles. Bulk vesicle preparations form plants show similarities with that of mammalian EVs, including a broad size-distribution (between 20 and 500 nm in diameter) and buoyant density. Bulk plant vesicles have been separated into a number of different vesicle populations by density gradient UC. Isolated nanovesicles have been studied for their cellular uptake, cytotoxicity, biological and therapeutic effects both *in vitro* [13, 15] and *in vivo* [13-15]. Mu *et al.* recently suggested that plant derived nanoparticles may have an active role not only in intra- and intercellular cargo delivery but also, when ingested, in interspecies communication between plant and mammalian cells which opens up new avenues for further exploitation. Vesicles from grape were shown to be efficiently taken up by intestinal stem cells and to induce tissue remodeling and protection against colitis [13]. Besides their direct use, plant nanovesicles are being exploited as a novel technology platform for loading and delivery of exogenous nutraceuticals and drugs too [14]. For example, grapefruit-derived nanovectors have been successfully used to load and deliver a variety of therapeutic agents including chemotherapeutic drugs, DNA expression vectors, siRNAs and antibodies to intestinal macrophages [16]. Edible plant derived nanovesicles in comparison with current drug delivery nanosystems, such as liposomes, gold nanoparticles, carbon nanotubes, polymeric nanoparticles, dendrimers, etc. show advantages in terms of naturally non-toxic origin, cellular uptake, biocompatibility and reduced clearance rates [17]. Moreover, large-scale production of plant nanovesicles is much more feasible than isolation of mammalian cell-derived EVs from culture media. Hence translation of plant-derived vesicles hold great promise for potential pharmaceutical, nutraceutical and cosmeceutical applications. In spite of their importance, at present we have only limited knowledge about the molecular composition and heterogeneity of the various vesicle populations isolated from plant tissues.

Citrus is one of the most important fruit crops in the world. Consumption of orange juice for example is associated with improved diet quality and positive health outcomes, including lower total cholesterol and low density lipoprotein levels. *Citrus limon* juice-derived nanovesicles were shown to inhibit cancer cell proliferation *in vitro* and *in vivo* through the activation of TRAIL-mediated apoptosis [15, 18]. Citrus species will likely become a major source of nanovectors in food and healthcare biotechnology. In this study, we isolated vesicle-like organelles from the fruit juice of four *Citrus* species: *C. sinensis*, *C. limon*, *C. paradisi* and *C. aurantium*. Micro- and nanovesicle fractions were separated, purified and their protein cargo were characterized and compared using a label free quantitative shotgun proteomics. The main aim was to identify elements of the highly complex

vesicular transport network and to shed light on the physiological and biological roles of the proteins present. A bioinformatics approach, including a comparative analysis with a recently published 'core set' of predicted vesicular transport proteins of *A. thaliana* and yeast corresponding to 240 factors [19] and proteins present in EVs databases [20] were used as baits to identify putative vesicular transport and EVs related components in citrus vesicles.

2. Material and methods

2.1 Plant material and vesicle isolation:

Fruits of four different Citrus species, sweet orange (*C. sinensis*), lemon (*C. limon*), grapefruit (*C. paradisi*) and bitter orange (*C. aurantium*) grown without any pre- and postharvest treatments were collected at maturity stage 3 from local gardens in Naples, Italy in July 2017. 5-10 pieces of fresh fruits were squeezed to obtain approximately 500 mL of fruit juice. Protease inhibitor cocktail containing cOmplete ultra tablets EDTA free (Roche, Mannheim, Germany) prepared according to manufacturer instruction, Leupeptine (0.25 mL, 1 mg/mL), 100 mM Phenylmethylsulfonyl fluoride (PMSF) (1.25 mL) and 1 M sodium azide (0.8 mL) were added to each samples. Vesicles were isolated in four parallel experiments by differential ultracentrifugation following the procedure described by Stanly *et al.* [21]. Briefly, low-velocity centrifugation steps were performed at 400 x *g* and 1000 x *g* for 20 min at 22 °C to eliminate cell debris, and at 15,000 x *g* for 20 min at 22 °C to collect the fraction enriched in microvesicles. The supernatant was ultracentrifuged at 150,000 x *g* for 60 min at 4 °C using a 70Ti Beckman rotor and the resulting pellet was set aside for nanovesicle purification. To remove co-purifying pectins, pellets obtained after the 15,000 x *g* and 150,000 x *g* centrifugation steps were solubilized in 50 mM Tris-HCl pH 8.6 and re-centrifuged two more times using the same centrifugal conditions. Finally, the Tris-HCl buffer was exchanged to PBS. Protein concentrations were measured by micro BCA assay (Thermo Scientific, Rockford, IL USA) using Nanodrop 2000 (Thermo Fisher Scientific Inc., Waltham, MA, USA). Samples were used fresh for subsequent characterization and proteomics experiments and then conserved at -80 °C.

2.2 Physiochemical characterization of different vesicle populations:

2.2.1 Transmission electron microscopy (TEM)

Samples were diluted to 1 µg/µL concentration using 0.1 M PBS pH 7.6 and five microliter aliquots were used for TEM analysis. The samples were deposited onto formvar and carbon coated 300 mesh copper grids for one minute. The preparation droplets were removed and the grids were dried. The samples were negatively stained with 2 % (w/v) aqueous uranyl acetate. TEM images were acquired by a Jeol JEM 1011 electron microscope operating at 60 kV and mounted with a Morada CCD camera (Olympus Soft Imaging Solutions).

2.2.2 Dynamic Light Scattering (DLS)

Vesicle size distribution was measured by dynamic light scattering (DLS) using a Zetasizer Ver. 7.01, Malvern Instrument (Malvern, UK). Each sample was dispersed in deionized water and the intensity of the scattered light was measured with a detector at 90° angle at room temperature. Mean diameter and size distribution were the mean of three measures.

2.2.3 Proteomics and data analysis

Protein profiling by SDS-PAGE:

The quality of vesicle samples was controlled using sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE). Samples (20 µg protein) were electrophoretically separated under reducing conditions on a precast Novex Bolt 4-12 % Bis-Tris Plus gel using Bolt MOPS SDS running buffer (Life Technologies, Carlsbad, CA, USA) according to the manufacturer's instructions and stained with colloidal Coomassie blue.

Shotgun proteomics analysis:

For *in-solution* proteomics analysis, samples (100 µg protein measured by micro BCA assay) were solubilized in 0.2 % RapiGest SF (Waters Corp., Milford, MA, USA) and vesicles were lysed using five freeze-thaw cycles under sonication in dry ice with ethanol. Proteins were reduced using 5 mM DL-Dithiothreitol (Sigma-Aldrich, Saint Louis, MO, USA,), alkylated using 15 mM Iodoacetamide (Sigma-Aldrich, Saint Louis, MO, USA), and digested using MS grade trypsin (Pierce, Thermo Sci.

Rockford, IL, USA) as described previously [21]. Samples were vacuum dried and solubilized in 5 % acetonitrile and 0.5 % formic acid (LC-MS grade, Thermo Sci. Rockford, IL, USA) prior to nano-HPLC-MS/MS analysis.

nanoLC-ESI-MS/MS:

Shotgun proteomics analysis was carried out on 1 µg of tryptic digest using a Dionex Ultimate 3000 nanoRSLC (Dionex, Sunnyvale, Ca, USA) coupled to a Bruker Maxis II mass spectrometer (Bruker Daltonics GmbH, Bremen, Germany) via CaptiveSpray nanobooster ionsource. Peptides were desalted on an Acclaim PepMap100 C-18 trap column (100 µm x 20 mm, Thermo Scientific, Sunnyvale, CA, USA) using 0.1 % TFA for 8 minutes at a flow rate of 5 µL/min and separated on the ACQUITY UPLC M-Class Peptide BEH C18 column (130 Å, 1.7 µm, 75 µm x 250 mm, Waters, Milford, MA, USA) at 300 nl/min flow rate, 48 °C column temperature. Solvent A was 0.1 % formic acid, solvent B was acetonitrile, 0.1 % formic acid and a linear gradient from 4 % B to 50 % B in 90 minutes was used. Mass spectrometer was operated in the data dependent mode using a fix cycle time of 2.5 sec. MS spectra was acquired at 3 Hz, while MS/MS spectra at 4 or 16 Hz depending on the intensity of the precursor ion. Singly charged species were excluded from the anaylsis.

Protein identification, quantitation and statistical analysis:

Raw data files were processed using the Compass DataAnalysis software (Bruker, Bremen, Germany). Proteins were searched using the Mascot software v.2.5 (Matrix Science, London,UK).against the NCBI *Citrus sinensis* database (88176 entries). The search criteria were the following: 7 ppm precursor and 0.05 Da fragment mass tolerance. Two miscleavages were allowed, and the following modifications were set: Carbamidomethylation on cysteine as fixed modification, while methionine oxidation and asparagine and glutamin deamidation as variable modifications. Protein identifications were validated by the Percolator algorithm [22], false discovery rate was < 1%. The default peak-picking settings were used to process the raw MS files in MaxQuant [23] version 1.5.3.30 for label free quantitation. Peptide identifications were performed within MaxQuant using its in-built Andromeda search engine. Heat map was generated by XLStat statistical software ad-in in Microsoft Excel [24].

Bioinformatics:

Functional annotation and data mining was performed using Blast2Go v.4.1.9 software including InterPro, enzyme codes, KEGG pathways, GO direct acyclic graphs (DAGs), and GOSlim functions

[25]. Identified proteins in FASTA format was used as input data. The Blastp-fast search algorithm was used via NCBI web service using taxonomy filter green plants (taxa: 33090, Viridiplantae), number of blast hits 20 and expectation value 1.0E-3. The InterPro domain searches were performed using the input FASTA files. The Blast hits of each protein sequence were mapped with Gene Ontology (GO) terms deposited in the GO database. Enzyme Code (EC) EC and KEGG annotations were performed on hits resulted in GO annotation. Venn diagrams were prepared using FunRich open access standalone software [26]. Orthology assignment and clusters for orthologous groups (COG) annotation were performed by EggNOg Mapper version 4.5.1 [27]. Functional annotation in EggNOG is based on fast orthology assignments using precomputed eggNOG clusters and phylogenies. EggNOG OGs were used to compare protein datasets between different taxa and EVPedia [20] deposited OGs. For the identification of vesicular transport related proteins in citrus vesicles, Sequence Bulk Download and Analysis tool (https://www.arabidopsis.org/tools/bulk/sequences/index.jsp) was used to retrieve the Arabidopsis Genome Initiative (AGI) locus identifiers of the recently published Arabidopsis core-set [19] into FASTA format using all gene model/splice form settings. FASTA file then was imported and analyzed by Blast2Go and EggNOG software.

3. Results and Discussion

3.1 Characterization of micro- and nanovesicles fractions of citrus-derived vesicles

The citrus juice sac cells originate from anticlinal and periclinal divisions of epidermal and subepidermal cells of the endocarp. The mature juice sac consists of an external layer of elongated epidermal and hypodermal cells which enclose large highly vacuolated and thin-walled juice cells [28]. Juice of citrus fruit contains a mixture of disrupted cells and cellular fluids. After removal of cells, cellular debris and large organelles, vesicle populations of the juices were separated into microvesicles (MVs) rich and nanovesicles (NVs) rich fractions using differential ultracentrifugation. Here, according to current EVs nomenclature vesicles were distinguished based on their size: MVs from 100 to 1,000 nanometers (nm) and NVs from 50 to 100 nm in diameter Based on BCA assay the different vesicle preparations contained variable amounts of proteins Protein concentrations, often used to estimate the

quantity of vesicles, were in the case of MVs 1445 mg kg^{-1} of grapefruit, 985 mg kg^{-1} of orange, 187 mg kg^{-1} of bitter orange and 94 mg kg^{-1} of lemon) and in the case of NVs 105 mg kg^{-1} of lemon, 52 mg kg^{-1} of orange, 32 mg kg^{-1} of grapefruit and 25 mg kg^{-1} of bitter orange

The MVs and NVs fractions were characterized by particle size distribution and morphology using DLS and TEM analysis (Figure 1 A and B) and by profiling of their respective protein biocargo using SDS-PAGE (Figure 1 C) and shotgun proteomics. Particles ranged in size from approximately 265 (grapefruit) to 950 nm (orange and bitter orange) in diameter were detected in the MV rich fraction by DLS. Vesicles found in the NV rich fractions showed a 2-mode distribution: the size of smaller particle populations ranged approximatively from 50 to 80 nm, while bigger vesicle groups measured from 350 to 700 nm (Figure 1 and Supplementary Figure 1-3). TEM confirmed that all the samples contained intact vesicles. Nucleus or other cellular compartments were not detected in these fractions. In accordance with the DLS findings, TEM analysis shows the presence of large particles in the MV fractions and similarly to DLS analysis, distinguish two particle populations in the NV enriched fractions as shown in Figure 1 B and Supplementary Figure 1-3. SDS-PAGE-based protein profiles of both MV and NV fractions of different citrus species are highly complex (Figure 1 C), an aspect that resembles to that of EVs isolated from mammalian cells. Protein patterns of the four different citrus species were similar to each other, but the SDS profiles of MVs and NVs were markedly different.

3.2 The protein cargo of different citrus vesicles

The protein cargo of vesicles is directly implicated in various events, like vesicle formation, curvature shaping, binding, as well as transfer of biological function to the membrane cell or donor organelle. The protein cargo of vesicles is packaged inside the lumen or it is part of the vesicle membrane (integral membrane proteins). In this study we applied organelle proteomics to identify the protein cargos of fruit sac cells-derived vesicle populations from four citrus species with the aim to compare them with existing datasets. Proteins were identified against a subset of the NCBI protein sequence database limited to *C. sinensis* taxonomy group and their expression levels were compared by means of label-free quantitative proteomics. *C. sinensis* taxonomy was chosen due to the successful completion of the sweet orange genome sequencing project in 2012 [29] and because it has the highest number of protein sequences amongst citrus species deposited in NCBI database. In each samples approximately 600-800 proteins were identified using the Mascot search engine (Supplementary Table 1 A and B).

Label-free protein quantitation was performed by MaxQuant to determine relative protein expression levels (Supplementary Table 2A). In the 8 samples analysed we have quantified altogether 1700 proteins. The Venn diagrams (Figure 1 D) display the numbers of unique and common proteins quantified in each sample. Altogether, there were 577 proteins in the MV and 440 proteins in the NV fractions commonly expressed by all the four species, and 389 proteins were mutual among the 8 samples analyzed. Orthologous groups (OGs) of each identified protein were predicted using EggNOG mapper [27]. OGs were used to compare our data to other taxonomically different datasets, and in particular to that of mammalian EVs related proteins deposited in EVPedia database [20]. Significant OG hits searched against the OG accession codes (23618 hits) published in EVPedia resulted in 769 overlapping OGs (Figure 2A) and 1408 associated protein hits. This indicates that a high percentage (87%) of the protein cargo of citrus vesicles mapped by EggNOG (i.e. 1408 out of the 1694 proteins listed in Supplementary Table 2B) were aligned to EVPedia. This set of proteins was considered to be relevant to the extracellular vesicle component (i.e. apoplastic vesicles) of NV and MV fractions. Similarly, we compared the predicted OGs associated to the protein cargo of the NV fractions of *C. limon* and *C. paradisi* to datasets from previous studies [15, 16] (Figure 2B). It should be noted that both studies have used gradient ultracentrifugation for the purification of the NVs after differential centrifugation yielding more homogeneous vesicle populations comparing to the NV fractions studied here. 57% of the OGs were found to be common in *C. limon* associated to 65% of the proteins identified by Raimondo *et al* and 35% of the OGs associated to 42% of the proteins identified by Wang *et al*, in the considerably smaller data set encompassing 98 proteins matched by EggNOG, in *C. paradisi* (Figure 2B and Supplementary Table 2B). These data indicate that beside the common set of proteins, the vesicular protein cargo of citrus is characterized by distinct features depending on, amongst other factors, the species, variants, samples, type of vesicle population as well as sample preparation method.

3.3 Candidate protein markers for citrus vesicles

EV research is facilitated by highly expressed EV marker proteins, like the tetraspanin family (CD9, CD63 and CD81), cytosolic proteins (such as heat shock 70 kDa protein, HSP70) and tumor susceptibility gene 101 protein (TSG101) which are frequently used in immunoblotting experiments and are useful to prove the vesicle character of a sample. Similar markers have not yet been described

for plant-derived vesicles. In this study, we analyzed the 20 top ranking proteins commonly identified in MVs and NVs fractions of juice sac cells to find marker candidates for these types of vesicles. Accession number of cluster of orthologous groups (COG) were determined and compared to that of "Top100 + EV marker" published in EVPedia database (http://student4.postech.ac.kr/evpedia2_xe/xe/) using identification count. Identification count is a number that reflects the frequency of identification of a given protein and its orthologues in EV datasets. We found that orthologues of most of the top ranking proteins in our data sets (18 out of 20 in both MV and NV fractions) have previously been identified in EVs (Table 1). This is in accordance with previous findings and shows that vesicles from different sources have a recurrent set of membrane and cytosolic proteins. In our set these are Enolase, HSP70, HSP80, 14-3-3 family proteins, glyceraldehyde-3-phosphate dehydrogenase (G3PD) and fructose-bisphosphate aldolase 6 (FBA6). These top-ranking proteins have very high EVPedia identification codes (higher than 400) and are amongst the 23 most frequently occurring orthologues.

Two fascinating plant proteins, *Patellin-3-like* and *clathrin heavy chain*, were found to be highly expressed in all the citrus samples (Table 1 and Supplementary Table 3A). *Patellin-3-like* is the most abundant protein in the citrus MV (Table 1A) and the second most abundant in the NV fractions (Table 1B). Patellins (PTLs) have been characterized in *Arabidopsis*, *zucchini* (*Cucurbita pepo*) and *Glycine max* [30] but not yet in citrus. PTL proteins share the typical domain structure that is a SEC14 lipid binding domain, a C-terminal Golgi dynamics domain (GOLD) and an acidic N-terminal domain. PTL member PTL3 is a plasma-membrane protein involved in vesicle/membrane-trafficking events associated with high cell division activity like cell plate formation during cytokinesis. PTL3 binds hydrophobic molecules such as phosphoinositides and promotes their transfer between the different cellular compartments. Most recently microarray-based approach demonstrated that PTLs play a fundamental role in cell polarity and patterning by regulating the auxin-induced PIN (Auxin efflux carrier family protein) relocation in *Arabidopsis thaliana* [31]. The presence of PTL in vesicular cargo is novel and its biological significance is worth further study. *Clathrins*, on the other hand, are well-known scaffold proteins that play a major role in the formation of clathrin coated vesicles (CCVs). CCV formation in mammals requires the assembly of a polyhedral cage composed of clathrin heteropolymers of heavy and light chains. CCVs mediate the vesicular transport from the trans-Golgi network/Early Endosome to the PM. Clathrin-mediated endocytosis (CME) as a major route of endocytosis in plant cells. The high abundance of *clathrin heavy chain-1* coat components in all of the

samples and the presence of *clathrin light chain 1-like* protein in *C. paradisi* and *C. limon* samples indicates that the isolated citrus sac cell vesicles are predominantly clathrin coated.

Interestingly, aquaporin, a protein frequently detected in mammalian extracellular vesicles was detected only in the NV fraction (Supp. Table 1A and 2A). Recently aquaporins have been reported to play an important role in vesicle stability in case of plasma membrane vesicles of broccoli plant. [32] Based on these observations, putative protein markers for plant vesicles are HSP70, HSP80, 14-3-3, G3PD and FBA6, PTL3 and clathrin proteins. On the other hand for plant nanovesicles a protein marker candidate is aquaporin. These proteins can facilitate the targeted functional and expression studies in the field of plant-derived vesicles.

3.4 Quantitative analysis of protein biocargo of citrus vesicles

A heat map chart in Figure 3 was generated using the MaxQuant output of the label-free shotgun analysis re-arranged according to clusters produced by hierarchical clustering. It shows the quantified proteins clustered in rows and the 8 citrus samples (MV and NV of 4 citrus species) in columns. By analyzing sample and protein dendrograms individually, it can be seen that the 8 samples are divided into two main groups (upper dendrogram). The clusters on the upper left and the upper right sides corresponds to the 4 MVs and the 4 NVs fractions, respectively. This shows that the vesicle cargo in different size vesicles result in a much larger difference, than that among the various citrus species. In the NV fractions *C. sinensis* and *C. paradisi* on the one hand, and *C. limon* with *C. aurantium* on the other hand show a large similarity. This corresponds well with philological relationship: *C. paradisi* is a hybrid of *C. sinensis* and *C. maxima*, while *C. limon* is a hybrid between *C. aurantium* and *C. medica*. In the left dendrogram proteins are divided into three major groups. The green and red large rectangles on the lower part of the map correspond to the first hierarchical cluster of proteins show a relatively high expression of this cluster of proteins in the MVs (green) and low expression in the NVs (red).

3.5 Heterogeneity of trafficking vesicles in citrus juice sac cells

Cellular vesicles are involved in the intra and inter cellular transport and communication events regulated by the secretory, recycling, endo- and exocytic pathways. Specialized proteins, for example, the components of endosomal sorting complexes required for transport (ESCRT), the Rab GTPases which are involved in regulation of vesicle formation and uncoating, and the SNAREs and tethering factors which aid the membrane fusion processes regulate these pathways. These proteins are located within the vesicle's coat or recruited from the cytosol while some others are expressed on the membrane surface of the vesicle-interacting cell or organelle. Plants have been shown to possess a high number of putative orthologues and paralogous for known genes that encode for the respective coat proteins [33], Rab GTPases [34], SNAREs [35] and ESCORTs [36]. Most vesicular transport related proteins in plants are predicted by bioinformatics and thus far only few of them have been experimentally identified. One such example is FREE1, which is a unique plant ESCRT component regulating multivesicular body protein sorting and plant growth in Arabidopsis [36]. Given the importance of vesicular trafficking for physiological [37] and pathological but also for environmentally triggered processes (like salinity, [38]), it is of prime importance to experimentally determine and characterize the expression of vesicular transport related proteins in plants. Here, we analysed the experimentally determined citrus juice sac cell related proteome using bioinformatics with the aim to identify vesicular trafficking machinery related proteins including vesicle coat proteins indicative of the type of trafficking vesicle (CCV, COPI and COPII). Proteins were indicated to be related to vesicular trafficking based on two different methods: 1) finding orthologues based on previously described vesicular transport proteins and 2) GO term enrichment analysis.

Recently, vesicular transport proteins of *A. thaliana* and yeast corresponding to 'core-set' of 240 factors (331 genes) has been used in an *in silico* study to detect putative proteins and group of (co-)orthologues in 14 plant species.[19] The 'core-set' contains 8 factors for the COPII, 16 for COPI, 18 for CCVs, 20 for Retromers and ESCRTs, 68 for Rab GTPases, 45 for Tethering factors and 65 for SNAREs. To determine putative vesicular transport related proteins and orthologue groups in the *C. sinensis* proteome, the Arabidopsis 'core-set' was translated into proteins using The Arabidopsis Information Resource (TAIR) database and used as a bait in B2Go blast search. 474 out of 489 Arabidopsis proteins yielded 1 to 20 blast hits and resulted altogether 1045 putative vesicular transport related proteins in *C. sinensis* (Supplementary Table 3A). Exploration of this set of proteins against the vesicular proteome of 4 citrus species identified in this work (Supplementary Table 1) resulted in 91 proteins (Supplementary Table 3B).

Additional putative vesicle related transport proteins of citrus were identified by extracting the proteins that are associated to GO terms “Transport) (GO:0006810) (Figure 4 A). Out of 299 proteins in our experimental data set associated with transport 96 were related to “vesicle-mediated transport” (GO:0016192). Comparing this with the set of proteins identified based on the ‘core-set’ of Arabidopsis (Figure 4 B) resulted in 119 putative vesicular related transport proteins (Supplementary Table 3B). Analysis of the dataset reveals the presence of proteins related to all the three main types of intracellular vesicles: CCV (8 proteins) and COPI (13 proteins) and COPII machineries related proteins (8 proteins). Coated vesicles (COPI, COPII and CCVs) are formed in a similar manner. The formation of vesicles is generally induced by a conformational change triggered by the exchange of guanosine diphosphate (GDP) to guanosine triphosphate (GDT) within a small GTPase. The GTPase recruits adaptor proteins, which in turn recruit coat proteins from the cytosol that polymerize to form the outer coat [39]. The presence of specific coat proteins thus is indicative of the type of vesicle.

COPI transport vesicles mediate retrograde transport from the Golgi to the ER and within the Golgi in the early secretory pathway. The key component of the COPI coat is a coatomer protein complex composed of seven subunits (α-, β-, β´-, γ-, δ-, ε- and ζ-COP) in eukaryotes. Several isoforms of α-, β-, β´-, ε- and ζ- subunits, but not isoforms for γ-COP and δ-COP subunits have been identified in Arabidopsis genome. Here we identified seven isoforms of α subunit of the outer layer of the of the COPI coat (Supplementary Table 3B). Other subunits of the COPI coatomer complex were not identified. In addition, six ADP-ribosylation factors (Arfs) could also be identified. Arfs are members of the ARF family of GTP-binding proteins of the Ras superfamily implicated in the regulation of COPI coat assembly and disassembly. Beside triggering the polymerization of the coat proteins and budding of the vesicles growing evidence supports the structural presence of Arf1 within the coat in COPI [40].

COPII intact spherical membrane vesicles are about 60–70 nm in size that carries protein cargo to the ER-Golgi intermediate compartment. The COPII polymerized coat includes five cytosolic proteins: Sar1, Sec23, Sec24, Sec13 and Sec31. The inner COPII coat is formed by the Sec23 and Sec24 hetero-dimers and the outer coat is constructed by Sec13 and Sec31 hetero-tetramers. In our experimental dataset homologues of all the five COPII coat proteins are present. Sar1 protein, a monomeric small GTPase regulates the assembly and disassembly of COPII coat and Sec12, of which homologue could also be identified in this work, is the guanine nucleotide exchange factor (GEF).

CCVs are produced at the TGN, endosomes and plasma membrane and are involved in various post-Golgi trafficking routes and endocytosis. Clathrin-mediated endocytosis is a well-established process not only in animal but also in plant cells. The outer shell of the CCV is a cage of interlocking clathrin triskelions, a large heterohexameric protein complex composed of three heavy and three light chains. Clathrin coat proteins are not able to bind directly to the membranes therefore their connection is mediated by so called clathrin adaptors. The AP complexes mediate both the recruitment of clathrin to membranes and play a central role in membrane trafficking by packaging cargo proteins into nascent vesicles. Arabidopsis genome encodes all subunits (adaptins) of five APs (AP-1 to AP-5). In our dataset 8 CCVs factors have been identified including the clathrin light and heavy chains coat proteins and subunits of adaptins AP-1, AP-2, AP-3 and AP-4. AP-1 is located at the TGN and involved in vacuolar trafficking and secretion in non-dividing cells, and trafficking to the cell plate from the TGN in dividing cells. AP-2 is involved in endocytosis from the PM and the cell plate. The AP-3 beta adaptin that mediates the biogenesis and function of lytic vacuoles in Arabidopsis was also identified in the dataset. In this work we do not identified homologues subunits of AP-5.

Other vesicular transport related proteins revealed in this study are Rab GTPAse (25 proteins), SNARE (18 proteins), tethering factors (12 proteins), retromer and ESCRTs proteins (15 proteins). Rab GTPase serves as master regulators of membrane trafficking starting from the formation of the transport vesicle till to its fusion at the target membrane. Specific Rab GTPAse is associated with each organelles. Her we identified 10 proteins from the largest RAB group called RABA1 that regulates transport between TGN and plasma mebrane. They all are isoforms of RABA1f proteins which gene in Arabidopsis is mainly expressed in flowers' pollen tube. SNAREs are membrane proteins that mediate fusion between vesicles and organelles to transport cargo molecules within the cells. Some SNAREs are localized in vesicles (called v-SNARE) while other SNAREs (called t-SNARE) are on the target organelle. Physically SNARE-SNARE interactions are thought to occur very selectively in the cells interaction between SNAREs localized in the target. Because selected members of the SNARE family proteins are localized in selected types of organelles.

Quantitative analysis of the 119 proteins potentially related to vesicle trafficking shows that the most abundant vesicle mediated transport related proteins when taking the average MaxQuant LFQ results of the 8 Citrus samples were RAB GTPases (37.3% of all transport related proteins), followed by CCVs (19.4%) and SNARE vesicles (14.5%). COPI and COPII related proteins were present in 7.5% and 4.0%, respectively. The top 30 most abundant transport related proteins were detected in at least 7 out

of the 8 samples. Analyzing the transport related proteins of the MV and NV fraction separately some differences appear. SNARE proteins are less abundant in the MV fraction (9.2%) than in the NV fraction (16.4%).

3.6 Ubiquity of hydrolases and oxidoreductases in citrus vesicles

Due to their efficient cellular uptake and lack of adverse immune reaction in human plant-derived vesicles are growingly exploited as nanovectors for the delivery of exogenous bioactive materials [14, 16]. Prior encapsulation, it is important to know the biological effects that unloaded vesicles trigger on their recipient cells. Natural plant-derived vesicles were shown to have significant biological effects, like inhibition of cell proliferation, apoptotic effect on cancer cell lines and induction of intestinal stem cells. [13, 15, 41] Amongst the potential effectors there are different enzymes that are commonly associated to the protein cargo of the vesicles. Enzymes present in vesicles being protected by the phospholipid membrane and has been shown to survive protein degradation events and reach recipient cells in their active forms. Upon their release they are prompt to catalyze a diverse array of biochemical reactions within the recipient cells. This prompted us to analyse the enzyme- content of citrus vesicles.

A high number of enzymes (482 proteins, Supplementary Table 4) were found by performing Enzyme class (EC) annotation of proteins identified in citrus vesicle samples. These belong to the 6 main enzyme classes (i.e. 1. oxidoreductases, 2. transferases, 3. hydrolases, 4. lyases, 5. isomerases, and 6. ligases). Figure 5 shows these enzyme classes are distributed in citrus vesicles. The two most representative enzyme classes accounting for more than the half of the enzymes identified (Supplementary Table 4) are class 3 hydrolyses and class 1 oxidoreductases. The role of fruit **hydrolases** in physiological processes like fruit ripening is well studied, thus their high expression in citrus juice sac cell derived vesicles was expected. Amongst the hydrolases, Adenosine triphosphatases (ATPases EC:3.6.1.3) acting on acid anhydrides are the most ubiquitous enzymes in the all the samples studied (Figure 6). We have identified 44 ATPases, including Vacuolar-type H + -ATPases (V-ATPases), calcium-, magnesium- and phospholipid-transporting ATPases (Supplementary Table 4). V-type ATPAse pumps protons across the plasma membrane and has function in acidification. ATP-driven proton pumps are cell membrane localized though they are also ubiquitous in intracellular organelles, such as endosomes, Golgi-derived vesicles, secretory vesicles, and vacuole. Recent studies proposed acidification-independent function of vesicular V-ATPases directly related to membrane

fusion and exocytosis [42] and thus their presence can give indications on the origin of EVs . Additionally, high number of hydrolases that act on peptide bonds (43 enzymes, EC 3.4 in Figure 5) were found, like the 20S core proteasome subunits. Proteasome subunits accumulate in some microvesicles and have been shown to that the proteasome is involved in the regulation of MV release [43]. We observed the accumulation of almost all the 20S complex units (proteasome alpha 1B, 2A, 3, 5, 6 and 7; proteasome beta 1, 2A, 3A, 4, 5, 6 and 7B). Other highly expressed hydrolases in citrus vesicles were pectinesterase, phospholipases, amylases, β galatosidases and adenosylhomocystein hydrolyse.

Enzymatic antioxidants are very important enzymes in protecting the cell from oxidative damage caused by reactive oxygen species (ROS) as by-products of redox reactions. Enzymatic antioxidants have important roles in scavenging ROS. Members of catalase (CAT), superoxide dismutase (SOD), peroxidase (POD), ascorbate peroxidase (APX) as well glutathione reductase (GPX) family enzymes were found to be highly expressed in all the studied vesicle preparations (Supp. Table 4). There is a growing body of evidence suggesting that oxidative stress plays a key role in the pathogenesis of numerous human diseases, such as cancer, autoimmune disorders, aging, rheumatoid arthritis, cardiovascular and neurodegenerative diseases. Given the importance of the management oxidative stress in disease there is a considerable interest in identifying novel enzymatic antioxidants. In this context, plant-made exogenous antioxidants of SODs, CATs or GPXs family enzymes readily packed into vesicles could have huge potential.

3.7 Conclusions

Vesicles preparations isolated from complex matrixes, such as fruit juice through ultracentrifugation and ultrafiltration steps contains highly heterogeneous populations of extracellular and intracellular membrane vesicles separated roughly by size and density. Study of citrus fruit sac cells-derived vesicles of four different citrus species show the presence of highly expressed HSP70, HSP80, 14-3-3, G3PD and FBA6, PTL3 and clathrin proteins in both MV and NV fractions. Aquaporin was found to be enriched mainly in the NV fraction. Based on specific characteristics of the composition of protein cargo, the heterogeneity of vesicles could be dissected into different vesicle subpopulations. A high percentage of isolated vesicles shows extracellular origin based on orthology search against proteins expressed in EVs of mammalian origin (Figure 2). In addition, different subpopulations of intracellular

vesicles, such as COPI, COPII and CCVs related to vesicular transport could be distinguished and characterized in citrus vesicles (Figure 4). Enzymes were highly expressed in both MV and NV fractions (Figure 5), and most significantly different hydrolases (ATPases, pectinesterase, phospholipases, amylases, β galatosidases and adenosylhomocystein hydrolyse) and enzymatic antioxidants (SODs, CATs, PODs and GPXs) were identified (Figure 6). Characterization of protein cargo of plant-derived vesicles is important in their exploitation as potential vectors for cellular delivery.

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