2

Lipid Droplets and Very Low Density Lipoproteins; Their Relation to Insulin Resistance

Sven-Olof Olofsson et al.*
Department of Molecular and Clinical Medicine and the Wallenberg laboratory
Sahlgrenska University Hospital/S, University of Gothenburg
Sweden

1. Introduction

1.1 Organization of the lipid droplet

Lipid droplets are organelles involved in the storage of neutral lipids, such as triglycerides or cholesterol esters. These molecules are neither soluble in water nor in the amphipathic monolayers that build up intracellular membranes, and are therefore stored in a separate hydrophobic "oil phase", which is the core of the lipid droplet. Since this is a general process, the ability to form lipid droplets is preserved throughout evolution and is present in most mammalian cells (Martin and Parton, 2006; Murphy and Vance, 1999; Olofsson et al., 2008; Olofsson et al., 2009).

The core of the lipid droplets is surrounded by a monolayer of amphipathic lipids, such as phospholipids and unesterified cholesterol (Martin and Parton, 2006; Olofsson et al., 2008; Olofsson et al., 2009). The monolayer is also associated with a number of different proteins, of which the best described and quantitatively most important are the PAT domain proteins (Dalen et al., 2007; Londos et al., 1999) (reviewed in (Brasaemle, 2007)), named after the first discovered members of the family i.e. perilipin, adipocyte differentiation-related protein (ADRP) and tail interacting protein 47 (TIP47). They are characterized by an amino-terminal PAT domain with a high degree of homology between the family members. Recent additions to the list of known PAT proteins include lipid storage droplet protein 5 (LSDP5; also known as OXPAT), myocardial lipid droplet protein (MLDP; also known as PAT-1) (Dalen et al., 2007; Wolins et al., 2006) and S3-12 (Dalen et al., 2004; Wolins et al., 2003).

1.1.1 Perilipin

Perilipin, which is mainly expressed in adipocytes and steriogenic cells (Londos et al., 1995), exists in three isoforms (perilipin A, B and C), which are formed from a single gene through

*Linda Andersson, Jeanna Perman, Mikael Rutberg, Lilliana Håversen, Li Lu, Emma Lu, Reza Mobini, Marcus Ståhlman, Susanna Myhre, Christina Olsson, Rosie Perkins,Thomas Larsson, Jan Borén and Martin Adiels.
Department of Molecular and Clinical Medicine and the Wallenberg laboratory Sahlgrenska University Hospital/S , University of Gothenburg, Sweden.

alternative splicing (Lu et al., 2001). Perilipin A is by far the most abundant and well-investigated isoform (Londos et al., 1999).
Perilipin has an important dual role in the turnover of triglycerides in lipid droplets It protects against triglyceride degradation when expressed in cells that lack natural expression of the protein (Brasaemle et al., 2000). Moreover, perilipin A-knockout mice show a substantial increase in basal lipolysis and reduction in adipose mass, and are resistant to diet-induced obesity (Martinez-Botas et al., 2000; Tansey et al., 2001). Perilipin also promotes triglyceride degradation: β-adrenergic stimulation does not promote lipolysis in perilipin A-knockout mice, and cells derived from these mice fail to show translocation of hormone-sensitive lipase (HSL) to the lipid droplet (Martinez-Botas et al., 2000; Tansey et al., 2001) (reviewed in (Londos et al., 2005)). A proposed model, based on these and more direct results (Granneman et al., 2007), states that concomitant phosphorylation of perilipin and HSL results in translocation of HSL to the lipid droplet where it catalyzes the hydrolysis of triglycerides (Granneman et al., 2007).
Perilipin also has an important role in the activation of adipose triglyceride lipase (ATGL), which catalyzes the first step in the degradation of triglycerides. Perilipin A interacts with CGI-58, the activator of ATGL (Lass et al., 2006). Phosphorylation of perilipin A promotes its dissociation from CGI-58, which will then associate with ATGL on lipid droplets to allow lipolysis (Granneman et al., 2007; Miyoshi et al., 2007).

1.1.2 ADRP

ADRP seems to play a central role in the assembly of lipid droplets even in perilipin-expressing cells such as the adipocyte. It is expressed in increasing amounts early in adipocyte differentiation, but is replaced by perilipin at later stages (Brasaemle et al., 1997).
In contrast to perilipin, ADRP is expressed ubiquitously (Brasaemle et al., 1997). The expression is highly related to the amount of neutral lipids in the cell (Heid et al., 1998), and overexpression of ADRP results in an increased formation of droplets (Imamura et al., 2002; Magnusson et al., 2006; Wang et al., 2003). The regulation of ADRP levels in the cell is complex. It is regulated at the transcriptional level by peroxisome proliferator-activated receptor α (PPARα) (Dalen et al., 2006; Edvardsson et al., 2006; Targett-Adams et al., 2003), but also through post-translational degradation by the proteasomal system (Masuda et al., 2006; Xu et al., 2005), which occurs when there are low levels of lipids in the cell. Thus, accumulation of intracellular triglycerides appears to stabilize ADRP and prevents it from being sorted to degradation.

1.1.3 TIP47

TIP47 was initially described as a ubiquitously expressed cytosolic and endosomal 47 kDa protein involved in the intracellular transport of mannose 6-phosphate receptors between the trans-Golgi and endosomes (Diaz and Pfeffer, 1998; Krise et al., 2000). TIP47 is believed to act as an effector for the Rab9 protein in this process, causing budding of vesicles directed to lysosomes (Carroll et al., 2001). TIP47 is also present on lipid droplets (Wolins et al., 2001). In contrast to ADRP, which is always associated with droplets and is degraded in the absence of neutral lipid, cytosolic TIP47 is shifted to lipid droplets in the presence of increased levels of fatty acids (Wolins et al., 2001).

1.1.4 LSDP5 (OXPAT)

LSDP5 is mainly expressed in tissues with high rates of β-oxidation, such as muscle, heart, liver, and brown adipose tissue (Wolins et al., 2006). Overexpression of LSDP5 in cultured

cells results in a substantial increase in the accumulation of triglycerides in response to fatty acid treatment (Wolins et al., 2006), which might be explained by a decrease in both basal and stimulated lipolysis (Dalen et al., 2007). Thus, LSDP5 seems to protect the triglyceride core of lipid droplets from degradation in a similar manner to perilipin. LSDP5 is transcriptionally regulated by PPARα in striated muscle and liver, and by PPARγ in white adipose tissue (Dalen et al., 2007; Wolins et al., 2006; Yamaguchi et al., 2006).

1.1.5 S3-12

S3-12 is mainly expressed in white adipose tissue, and it shares only a weak sequence homology with the PAT proteins (Wolins et al., 2003). S3-12 expression is transcriptionally regulated by PPARγ (Dalen et al., 2004).

1.1.6 Other lipid droplet-associated proteins

Several other proteins have also been described on lipid droplets (Brasaemle et al., 2004; Cermelli et al., 2006; Liu et al., 2004). They are involved in processes such as sorting/transport (e.g. RABs, ARFs, SNARE proteins and motor proteins), lipid biosynthesis [e.g. acyl-CoA synthetase, diacylglycerol acyltransferase (DGAT), acyl-CoA synthase and lanosterol synthetase] and lipid turnover [e.g. ATGL and its co-activator CGI-58, HSL, and cytosolic phospholipase A_2 (cPLA$_2$)] (reviewed in (Olofsson et al., 2009).
Caveolin and vimentin have been proposed to be present on lipid droplets (Brasaemle et al., 2004; Franke et al., 1987; Liu et al., 2004), but their function is not understood. One suggestion is that the presence of caveolin reflects an involvement of caveolin-rich plasma membranes in the assembly of lipid droplets (Ost et al., 2005). Caveolin has also been linked to triglyceride lipolysis in the droplets (reviewed in (Martin and Parton, 2006)). There are several other lipid droplet-associated proteins with functions that are yet to be elucidated.

1.2 Assembly of lipid droplets

Lipid droplets are formed from microsomal membranes (Brown, 2001). The main driving force in the assembly process is the formation of triglycerides (Marchesan et al., 2003; Stone et al., 2009) and all stimuli that promote triglyceride biosynthesis will therefore also promote the formation of lipid droplets. Other factors important for the assembly process include phospholipase D_1 (PLD$_1$) (Andersson et al., 2006; Marchesan et al., 2003), which catalyzes the formation of phosphatidic acid, a lipid that is essential for lipid droplet assembly (Andersson et al., 2006; Marchesan et al., 2003). PLD$_1$ contains a pleckstrin homology (PH) domain that is targeted by phosphatidylinositol (4,5) bisphosphate (PI(4,5) P2), which is essential for PLD$_1$ activity (McDermott et al., 2004; Powner and Wakelam, 2002). Additional targets for PI(4,5)P_2 that have been identified as important for lipid droplet formation include ARF1 (and proteins involved in the regulation of its activity) (Guo et al., 2008) and cPLA$_2$ (Gubern et al., 2008).
We have shown that lipid droplet formation also requires extracellular regulated kinase 2 (ERK2), which phosphorylates the motor protein dynein and thereby sorts it to lipid droplets (Andersson et al., 2006). The lipid droplets are then able to contact microtubules and are thus transported towards the center of the cell (Bostrom et al., 2005). Movement in both directions has been demonstrated (Bostrom et al., 2005; Welte et al., 1998). Our results clearly show that dynein is essential for lipid droplet fusion (see below), but also indicate that dynein is involved in the initial formation of the droplet (Andersson et al., 2006). The

details of this latter process have not been elucidated, but one possibility is that dynein provides a "pull force" that is necessary for the budding of droplets from the microsomal membrane.

The mechanism for the creation of cytosolic lipid droplets from the ER is not fully elucidated. One mechanism that was proposed several years ago (but without substantial experimental evidence) suggests that, upon formation, triglycerides are 'oiled out' between the leaflets of the microsomal membranes to form a lens that will become the core of the primordial lipid droplet. The rationale behind this model is that whereas the triglyceride precursors (diglycerides and acylCoA) are highly soluble in the cytosolic leaflet of the microsomal membrane, triglycerides have limited solubility in this leaflet and are therefore forced into the hydrophobic part of the membrane (Figure 1) (Brown, 2001; Olofsson et al., 2008).

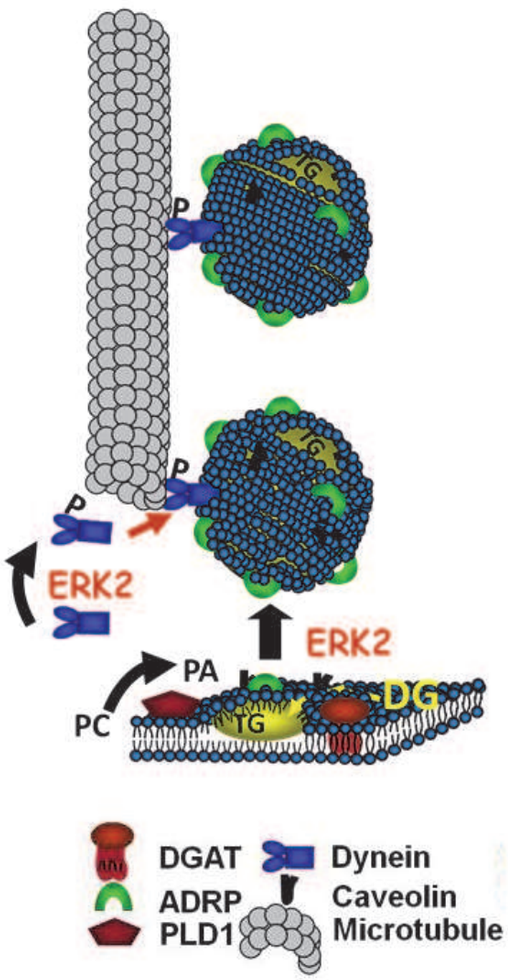


Fig. 1. Lipid droplets are formed from microsomal membranes. The assembly is driven by triglyceride formation from diglycerides, which is catalyzed by DGAT. The assembly process also requires PLD_1 and the formation of phosphatidic acid and ERK2. ERK2 phosphorylates dynein, which is then sorted onto droplets allowing them to migrate on microtubules.

1.3 Growth of lipid droplets

Newly synthesized lipid droplets are only 0.2 μm in diameter (Brown, 2001). However, mature lipid droplets are much larger (1-20 μm in diameter), indicating that they are able to grow after their formation. DGAT, which catalyzes the conversion of diglycerides to triglycerides, and the ongoing biosynthesis of triglycerides are essential for this process. It has been suggested that the surface of lipid droplets contains DGAT2, and thus the droplets may acquire triglycerides by direct biosynthesis (Kuerschner et al., 2008). However, because DGAT2 is known to span a bilayer twice (Stone et al., 2006), substantial adaptation of the enzyme would be required if it were to fit into the monolayer surface of the lipid droplet.

We demonstrated that lipid droplets can grow by fusion (Figure 2), and that approximately 15% of all droplets are engaged in the fusion process at a given time (Bostrom et al., 2005). The importance of this process, however, cannot be completely understood until we establish methods to follow the smallest lipid droplets by time lapse studies. Our very preliminary observations indicate that the fusion rate is highest among these primordial droplets. An interesting implication of fusion is that it likely involves droplets at all stages, and thus the larger droplets could have a relatively rapid connection with the DGAT2-dependent formation of the primordial lipid droplets in the microsomal membrane (Figure 3)

In addition to its dependence on dynein (Andersson et al., 2006; Bostrom et al., 2005), we have shown that lipid droplet fusion also involves the SNARE proteins synaptosomal-associated protein of 23 kDa (SNAP23), syntaxin-5 and vesicle-associated protein 4 (VAMP4) (Bostrom et al., 2007) and proteins involved in their regulation, namely the ATPase N-ethylmaleimide-sensitive factor (NSF) and α-soluble NSF adaptor protein (α-SNAP) (Bostrom et al., 2007). Recent results demonstrate that the ARF-like GTPase ARFRP1 is involved in determining the size of the droplets by sorting SNAP23 to lipid droplets (Hommel et al., 2010).

The role of the SNARE proteins, NSF and α-SNAP in fusion processes has primarily been investigated in the fusion between transport vesicles and target membranes. Central to this process is the formation of a four-helix bundle between α-helical domains present in the SNAREs (SNARE domains), which forces the membranes together promoting their fusion. A detailed molecular model of this process has recently been proposed (Giraudo et al., 2009; Sudhof and Rothman, 2009). The stable four-helix bundle present after the completed fusion is unwound by NSF and α-SNAP (for reviews, see (Hong, 2005; Jahn and Scheller, 2006; Malsam et al., 2008; Sudhof and Rothman, 2009)).

It is important to note that the presence of SNARE proteins on lipid droplets and the described fusion process open up the possibility for interactions with other organelles. Thus, fusion between a lipid droplet and the outer monolayer of the bilayer around a peroxisome may theoretically result in a structure very similar to that suggested to be formed between these two organelles (Binns et al., 2006). Further investigation is required to determine whether fusion accounts for the relatively tight interaction between lipid droplets and other organelles such as mitochondria (Shaw et al., 2008), peroxisomes (Binns et al., 2006) and the endoplasmic reticulum (ER) (Ozeki et al., 2005).

1.4 Lipid droplets and insulin resistance

Systematic insulin resistance is highly related to ectopic lipid accumulation, i.e. the accumulation of triglycerides in non-adipocytes such as liver, skeletal muscle and macrophages. Here, we focus on skeletal muscle, which is the tissue with the highest insulin-dependent consumption of glucose and thus of major importance in the development of insulin resistance.

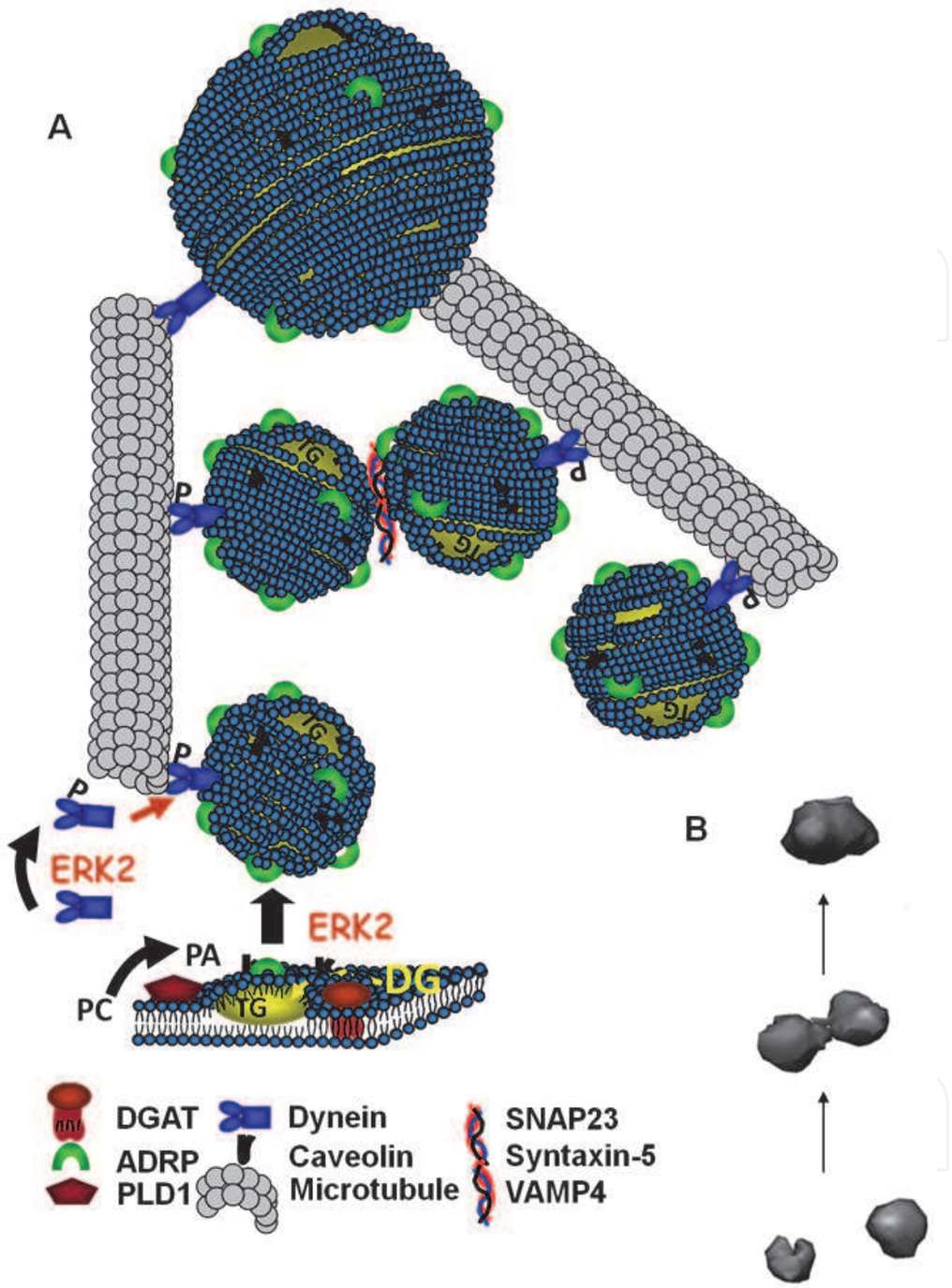


Fig. 2. The migration of lipid droplets on microtubules is important for the fusion between the droplets. This fusion is catalyzed by the SNARE proteins SNAP23, syntaxin-5 and VAMP4. (A) A schematic view of the fusion process. (B) A time lapse study of the fusion between two droplets. The process was viewed by confocal microscopy and three dimensional structures of the droplets were constructed as described in (Andersson et al., 2006).

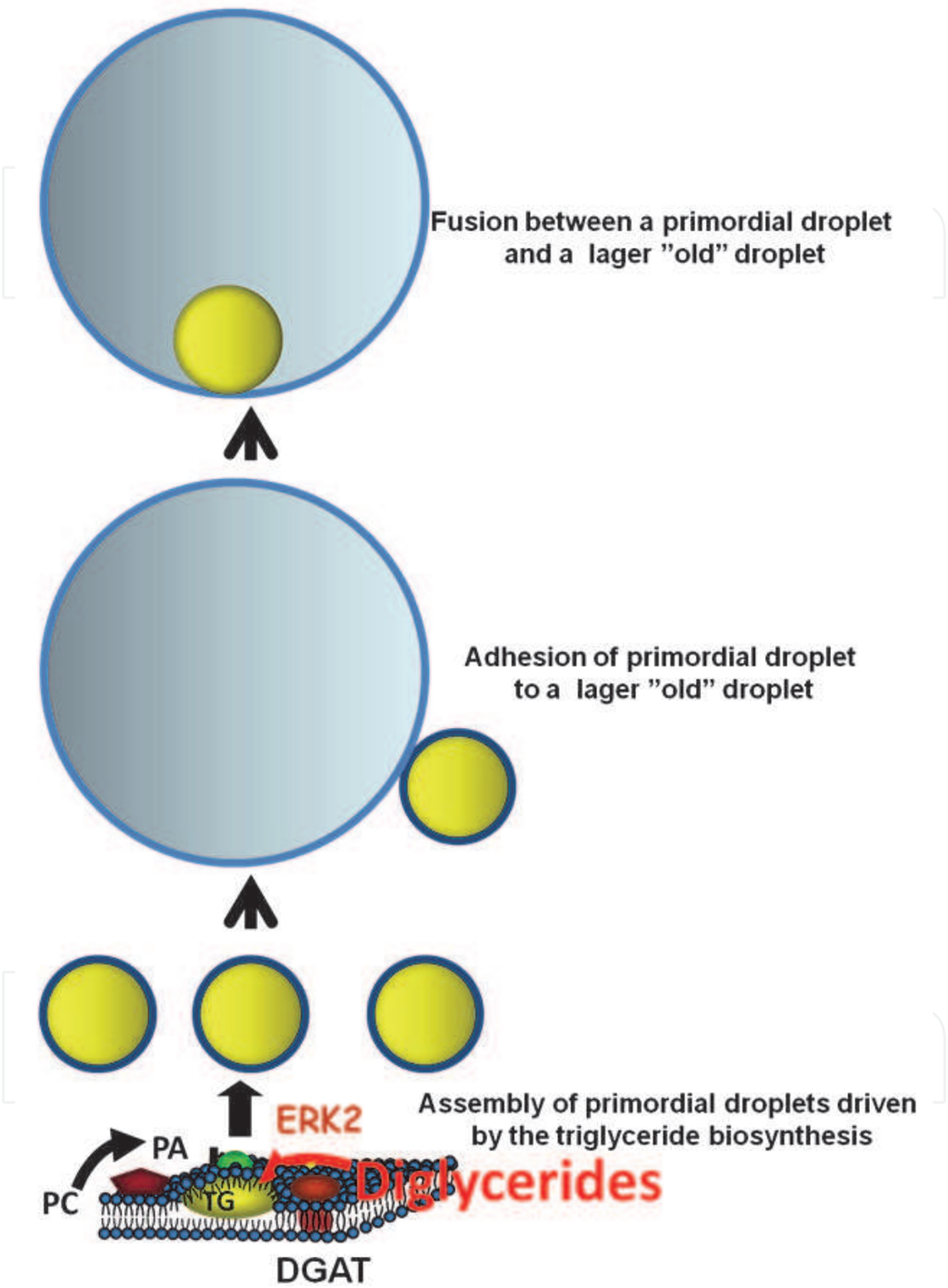


Figure 3. The fusion process allows small droplets to fuse with larger droplets. The primordial droplets formed by triglyceride biosynthesis in the microsomal membrane can fuse with larger "old" droplets and thus provide these droplets with newly synthesized triglycerides.

The strong correlation between lipid droplet accumulation in skeletal muscle and insulin resistance was for many years used as evidence that such accumulation causes insulin resistance. However, endurance-trained athletes also accumulate triglycerides in their skeletal muscle but are extremely insulin sensitive. This "athletes paradox" (Goodpaster et al., 2001; van Loon and Goodpaster, 2006) was one of the indications that the accumulation of triglycerides per se was not the problem but rather products of triglycerides such as fatty acids. Indeed, the accumulation of triglycerides in droplets has been regarded to be the result of a surplus of fatty acids in the cell. Moreover, it has been proposed that insulin resistance and inflammation are prevented by forcing fatty acids into droplets by increasing the levels of DGAT (Koliwad et al., 2010).

Several products of fatty acids have been linked to the development of insulin resistance, including partially oxidized fatty acids (Koves et al., 2008), ceramides (reviewed in (Summers, 2006)) and diglycerides (reviewed in (Samuel et al., 2010). The mechanism behind the influence of the two first is not known in detail, but diglycerides are known to impair insulin signaling through activation of protein kinase C θ (PKCθ). PKCθ phosphorylates insulin receptor substrate I, thus preventing the phosphorylation involved in the insulin signal for details, see (Samuel et al., 2010).

Fatty acids can also directly influence the insulin-dependent recruitment of the glucose transporter 4 (GLUT4) to the plasma membrane though their influence on SNAP23 (Bostrom et al., 2007). As described above, SNAP23 is a SNARE protein that is involved in lipid droplet fusion, but it also plays a central role in insulin-dependent glucose uptake in skeletal muscle and adipose tissue. SNAP23 together with syntaxin-4 form a target SNARE complex, which interacts with the vesicle SNARE VAMP2 on GLUT4-specific vesicles (GSV) and thus allows GSV to fuse with the plasma membrane upon insulin stimulation. GLUT4 is thereby directed to the plasma membrane, thus increasing the glucose uptake.

We demonstrated first in cells that fatty acids displace SNAP23 from the plasma membrane (and the fusion of GSV) to the interior of the cell, resulting in insulin resistance (Bostrom et al., 2007). We translated these results into humans by studying skeletal muscle biopsies from patients with type 2 diabetes and lean and obese controls (Bostrom et al., 2010). In agreement with our results in cells, we observed that triglyceride accumulation in human skeletal muscle is accompanied by both insulin resistance and redistribution of SNAP23 from the plasma membrane to the interior of the cell (Bostrom et al., 2010).

1.5 Lipid droplets in hypoxia/ischemia

Both human macrophages and heart muscle cells that are exposed to hypoxia accumulate lipid droplets. In both cell types, lack of oxygen results in a decrease in the oxidation of fatty acids, an increase in glycolysis and lactate production and increased triglyceride biosynthesis. Thus, the accumulation of lipid droplets seems to be part of a mechanism that adapts the metabolism to minimize oxygen consumption.

Macrophages are exposed to hypoxia in both atherosclerotic lesions (Bjornheden et al., 1999) and adipose tissue (Donath and Shoelson, 2011; Trayhurn et al., 2008; Ye, 2009). Thus, the described mechanism may be of importance for creating lipid-loaded macrophages (foam cells) in atherosclerotic lesions and in the adipose tissue of obese individuals. It is well known that cholesterol from low-density lipoproteins (LDL) contributes to the lipid droplet formation in macrophages in the arterial wall. The mechanism involving modified LDL and scavenger

receptor(s) has been described in detail elsewhere (see for example (Greaves and Gordon, 2005). However, it should be noted that macrophages from atherosclerotic lesions contain high levels of triglycerides (Mattsson et al., 1993). Adipose tissue hypoxia results in macrophage recruitment and has a role in the inflammation seen in the adipose tissue during insulin resistance/type 2 diabetes (Donath and Shoelson, 2011; Trayhurn et al., 2008; Ye, 2009).

We have shown that accumulation of lipid droplets in hypoxic macrophages promotes the formation and secretion of eicosanoids and chemokines by recruiting $cPLA_2$ to the lipid droplet surface (Bostrom et al submitted). $cPLA_2$ catalyzes the production of arachidonic acid, which is the precursor of eicosanoids. Thus, triglyceride accumulation in hypoxic macrophages induces inflammation. By contrast, triglyceride accumulation caused by increased expression of DGAT1 in macrophages prevents insulin resistance and inflammation (Koliwad et al., 2010). This difference suggests that the triglyceride storage seen in hypoxia may be accompanied by a surplus of lipotoxic fatty acids, ceramides and diglycerides that have not been metabolized. Because DGAT1 promotes the conversion of diglycerides to triglycerides, increased levels of DGAT1 will likely promote the conversion of lipotoxic lipids to a hydrophobic, inert lipid that is safely stored in lipid droplets.

We have also shown that the hypoxia/ischemia-induced accumulation of triglyceride-containing lipid droplets in heart muscle cells is completely dependent on the VLDL receptor, which promotes the endocytosis of triglyceride-rich lipoproteins (Perman et al., 2011). Hypoxia-induced VLDL receptor expression is dependent on hypoxia-inducible factor 1α through its interaction with a hypoxia-responsive element in the promoter of the VLDL receptor (Perman et al., 2011). We also observed an increased accumulation of lipid droplets and a parallel increase in expression of the VLDL receptor in biopsies from ischemic left ventricle from human hearts compared with biopsies from non-ischemic left ventricles (Perman et al., 2011).

The VLDL receptor induced accumulation of lipid droplets during hypoxia/ischemia is accompanied by increases of both ER stress (which is at least partly caused by increased formation of long chain ceramides) and apoptosis in mouse hearts (Perman et al., 2011). Importantly, VLDL receptor knockout mice have improved survival in response to an acute myocardial infarction than wildtype mice (Perman et al., 2011). Thus, the VLDL receptor and the accumulation of lipid droplets seen in hypoxia/ischemia are potential targets for treatment against early death following an acute myocardial infarction.

2. The secretion of triglycerides

Triglycerides are mostly secreted from the intestine and liver as triglyceride-rich lipoproteins, which have an organization that is very similar to the lipid droplets. Thus, they consist of a core of the neutral lipids surrounded by a monolayer of phospholipids, cholesterol and proteins (known as apolipoproteins). The primary apolipoprotein is apoB, which is required for the formation of lipoproteins. It exists in two forms: apoB48 on chylomicrons (the lipoproteins formed in the intestine); and apoB100 on very low-density lipoproteins (VLDL; the lipoproteins formed in the liver). Here we focus on the formation of VLDL.

The secretory pathway

As for other secretory proteins, apoB is synthesized on ribosomes attached to the surface of the ER (Figure 4) and the 'nascent' polypeptide is translocated through a channel

(reviewed in (Johnson and Haigh, 2000; Johnson and van Waes, 1999)) to the lumen of the ER, where it is folded into its correct structure with the help of chaperone proteins. When folded correctly, the secretory proteins are sorted into exit sites to leave the ER by transport vesicles. Failure to fold results in retention in the ER and retraction through the membrane channel followed by sorting to proteasomal degradation (Ellgaard and Helenius, 2001; Ellgaard and Helenius, 2003; Ellgaard et al., 1999; Johnson and Haigh, 2000; Johnson and van Waes, 1999; Kostova and Wolf, 2003; Lippincott-Schwartz et al., 2000).

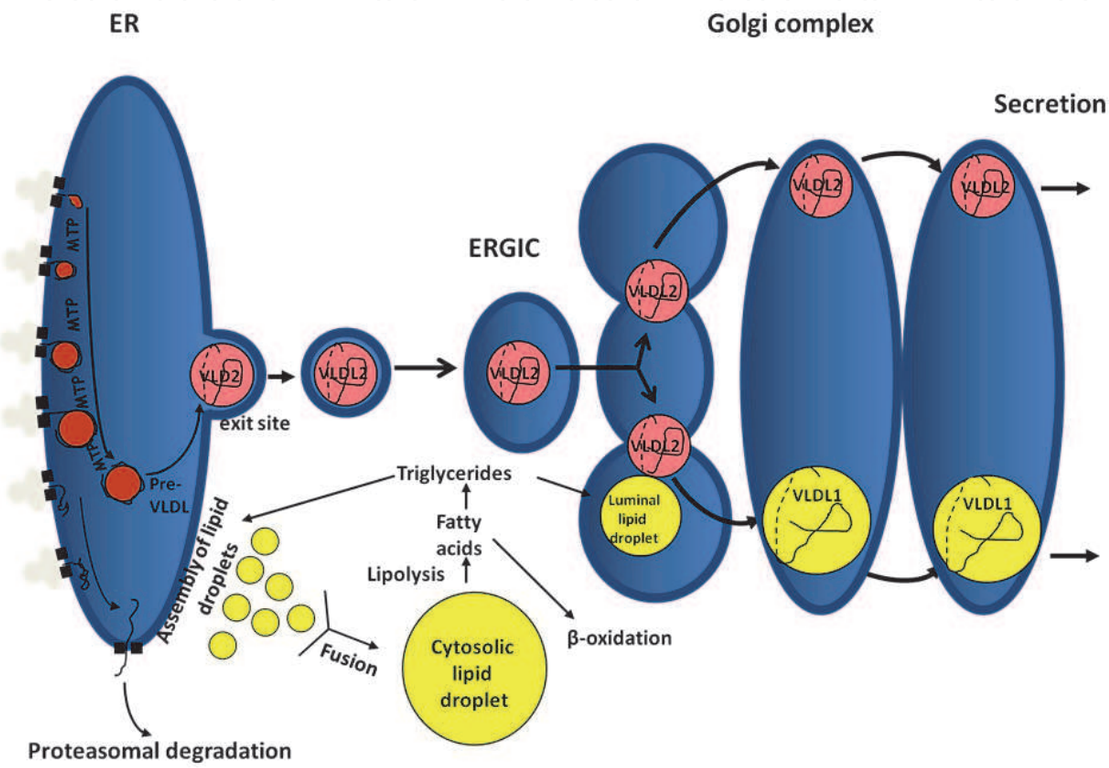


Fig. 4. The formation of VLDL1 and VLDL2. ApoB is formed on ribosomes attached to the ER and translocated to the lumen of the ER. During this translocation, the protein is lipidated by the microsomal triglyceride transfer protein (MTP) to form pre-VLDL. If this lipidation is inadequate, apoB is sorted back to the cytosol to be degraded by proteasomes. By post-translational lipidation, the pre-VLDL forms VLDL2, which is allowed to leave ER through exit sites. Pre-VLDL that is not converted to VLDL2 will be sorted to degradation (most likely by autophagocyty). VLDL2 is translocated through the secretory pathway and is either secreted or converted to VLDL1 in the Golgi apparatus by bulk lipidation, a process that is highly dependent on the amount of triglycerides that is stored in the cell.

The vesicles that bud off from the ER exit sites form the ER Golgi intermediate compartment (ERGIC), which is involved in protein sorting. ER-specific proteins are returned to the ER from the ERGIC and are thereby prevented from entering the later part of the secretory pathway. The ERGIC matures into cis-Golgi, which undergoes 'cisternal maturation' to form the medial- and trans-Golgi apparatus. During this maturation, proteins that will be secreted are transferred through the Golgi stack. Finally, the proteins are transported from

the trans-Golgi to the plasma membrane for secretion (reviewed in (Elsner et al., 2003; Kartberg et al., 2005)).

2.1 The assembly of VLDL

The assembly of VLDL involves three types of particles: a primordial lipoprotein (pre-VLDL), a triglyceride-poor form of VLDL (VLDL2) and a triglyceride-rich atherogenic form of VLDL (VLDL1) (Stillemark-Billton et al., 2005).

2.1.1 The primordial lipoprotein

The assembly process starts when the growing apoB100 is cotranslationally lipidated by MTP in the lumen of the ER (Figure 4), resulting in the formation of a dense, partially lipidated form of apoB100 that is retained in the cell (Boström et al., 1988; Stillemark-Billton et al., 2005). This product, which we refer to as primordial lipoprotein (or pre-VLDL), is a precursor to VLDL2 and VLDL1.

The appearance of the apoB100 primordial lipoprotein is highly dependent on the C-terminal region of apoB100 (Stillemark-Billton et al., 2005). Moreover, the particle is highly associated with chaperone protein such as binding proteins (BiP) and protein disulfide isomerase (PDI). A potential explanation is that regions in the C-terminal of apoB100 sense the degree of lipidation and anchor the partially lipidated particle to chaperones, which retain the particle in the ER. Once the level of lipidation is sufficient to allow apoB100 to fit on the particle and the C-terminal to fold correctly, the chaperones dissociate and the particle can transfer out of the ER. Thus, the primordial lipoprotein is either retained in the cell and degraded (if not sufficiently lipidated) or further lipidated to form VLDL2 (Figure 4) (Olofsson and Asp, 2005; Olofsson et al., 1999; Olofsson et al., 2000; Stillemark-Billton et al., 2005).

2.1.2 VLDL2

VLDL2 formation is highly dependent on the length of apoB, and truncated forms of apoB result in the formation of denser particles (Stillemark et al., 2000). Indeed, there is an inverse relation between the density of the lipoproteins formed and the length of apoB. *Bona fide* VLDL2 is only formed with apoB100. The lipoprotein formed by apoB48 (which is produced only in the intestine in humans but in both the intestine and liver in mice) has the same density as high-density lipoprotein (HDL) (Stillemark-Billton et al., 2005). However, despite having the same density as apoB100 pre-VLDL (which is retained in the cell unless further lipidated), the dense lipoprotein formed by apoB48 is secreted and behaves in the same way as a VLDL2 particle formed by apoB100. We therefore propose that it is a VLDL2 analog. Thus, both *bona fide* VLDL2 and VLDL2 analogs can be either secreted or further lipidated to form VLDL1 (Fig 4).

2.1.3 VLDL1

VLDL1 is formed from VLDL2 by a second type of lipidation in which the VLDL2 particle receives a bulk load of lipids in the Golgi apparatus (Stillemark-Billton et al., 2005). We have detected a precursor-product relationship between VLDL2 and VLDL1 both in cell cultures (Stillemark-Billton et al., 2005) and turnover experiments in humans (Adiels et al., 2007).

In contrast to the formation of VLDL2, apoB only needs to have a minimum size of apoB48 to allow the conversion to VLDL1 (Stillemark-Billton et al., 2005). We have recently demonstrated that the sequence close to the C-terminal of apoB48 is essential for the VLDL1 formation. We have identified a protein (BAP31) that interacts with this sequence and promotes the formation of VLDL1 (Beck et al. Manuscript in revision).

The formation of VLDL1 is dependent on the GTPase ARF1, a protein that is required in the anterograde transport from ERGIC to cis-Golgi (Asp et al., 2000). This is consistent with results showing that VLDL1 formation occurs in the Golgi apparatus (Stillemark et al., 2000), and indicates that the formation of VLDL1 requires a transfer of apoB100 from the ER to the Golgi apparatus (Figure 4). Thus, one would expect a time delay of approximately 15 min between the biosynthesis of apoB100 and the major addition of lipids to form the VLDL1 particle. Indeed, in turnover studies in humans, we confirmed the presence of two steps in the assembly of VLDL1 with a 15 min difference between the secretion of newly formed apoB100 and newly formed triglycerides (Adiels et al., 2005b).

It has been suggested that the formation of lipid droplets in the lumen of the secretory pathway plays a central role in VLDL assembly, i.e. lipid droplets fuse with apoB to form VLDL (Alexander et al., 1976). This is an interesting hypothesis that still remains to be tested, particularly in terms of elucidating the mechanism by which a luminal lipid droplet is formed and how it fuses with VLDL2. The proposed mechanism may link the assembly of the core of VLDL1 to the process by which the core of a cytosolic lipid droplet is assembled. It has been proposed that the assembly of a droplet starts in the hydrophobic portion of the microsomal membrane with the formation of a triglyceride lens, which is then released into the cytosol. A triglyceride lens may also bud into the lumen of the secretory pathway, thereby giving rise to a luminal droplet that becomes the core of VLDL. This hypothesis remains to be tested experimentally (Brown, 2001; Murphy and Vance, 1999; Olofsson et al., 1987).

Several authors have demonstrated that fatty acids used for the biosynthesis of VLDL triglycerides are derived from triglycerides stored in cytosolic lipid droplets (Gibbons et al., 2000; Salter et al., 1998; Wiggins and Gibbons, 1992), and that enzymes involved in the release of such fatty acids have an influence on the formation of VLDL (Dolinsky et al., 2004a; Dolinsky et al., 2004b; Gilham et al., 2003; Lehner and Vance, 1999; Trickett et al., 2001).

2.2 VLDL assembly in type 2 diabetes

A major factor in the development of the dyslipoproteinemia seen in type 2 diabetes is the increased secretion of VLDL1 (Taskinen, 2003). This secretion has important implications for the formation of small dense LDL and the low levels of HDL. Below, we will discuss possible mechanisms for the increased secretion of VLDL1 during type 2 diabetes.

Using stable isotope techniques, we and others (Adiels et al., 2006; Fabbrini et al., 2009; Fabbrini et al., 2008) have repeatedly shown a relationship between liver fat content and secretion of VLDL particles. Thus, the major determinant for the secretion of VLDL1 is the amount of triglycerides in the liver. An accumulation of ectopic triglycerides in the liver is a major event in the development of insulin resistance/type 2 diabetes. Thus, lipids in the liver link type 2 diabetes to increased secretion of VLDL1.

Another factor of importance is insulin. Although insulin inhibits the assembly of VLDL1 in individuals with low liver lipid levels, insulin does not have a similar effect in patients with

high liver lipid levels (Adiels et al., 2007). These findings are in agreement with lipid accumulation in the liver being the most important regulator of VLDL1 assembly.
Several possibilities to explain why insulin inhibits VLDL1 formation have been summarized previously (Taskinen, 2003). One potential reason is that insulin inhibits lipolysis in adipose tissue and thereby decreases the inflow of fatty acids to the liver. Support for an influence on the lipolysis in the adipose tissue was obtained from studies using nicotinic acid analogs (reviewed in (Taskinen, 2003)).
Insulin is also known to promote the formation of lipid droplets (Andersson et al., 2006). Thus, it is possible that insulin diverts triglycerides from the bulk lipidation of VLDL2 to the formation of lipid droplets. Indeed, we have observed other situations where promoting the formation of lipid droplets inhibits VLDL1 assembly. For example, increased levels of ADRP in the cell result in increased storage of neutral lipids in lipid droplets and reduces their entry into the assembly pathway (Magnusson et al., 2006). Such a manipulation results in decreased VLDL1 production, despite increased levels of triglycerides in the cell. In addition, increasing the rate of fusion between droplets results in decreased VLDL secretion and an increased number of droplets in the liver cell (Li et al., 2005).

2.3 ApoB100 degradation

It has long been known that apoB100 undergoes intracellular degradation (reviewed in (Davidson and Shelness, 2000; Olofsson et al., 1999; Shelness and Sellers, 2001)). The degradation is dramatically reduced when the supply of fatty acids (and the biosynthesis of triglycerides) is increased (Borén et al., 1993; Boström et al., 1986) and it is known that post-translational degradation is important for the regulation of the secreted apoB. The intracellular degradation of apoB100 occurs at three different levels (Fisher and Ginsberg, 2002; Fisher et al., 2001): (i) close to the biosynthesis of apoB (co- or post-translationally) by a mechanism that involves retraction of the apoB molecule from the lumen of the ER to the cytosol (through the same channel as it entered during its biosynthesis), ubiquitination and subsequent proteasomal degradation (Fisher et al., 2001; Liang et al., 2000; Mitchell et al., 1998; Pariyarath et al., 2001); (ii) post-translationally by an unknown mechanism that seems to occur in a compartment separate from the rough ER, and is referred to as post-ER presecretory proteolysis (PERPP) (Fisher et al., 2001); (iii) by reuptake from the unstirred water layer around the outside of the plasma membrane (Williams et al., 1990) via the LDL receptor. The LDL receptor has been shown to have an important role in regulation of the secretion of apoB100-containing lipoproteins (Horton et al., 1999; Twisk et al., 2000).
Interestingly, the PERPP has been linked to the autophagocytic pathway (Pan et al., 2008). Contrary to post-translational degradation which targets proteins, the autophatocytic pathway allows the degradation of particles, such as pre-VLDL and VLDL.
The intracellular degradation of apoB seems to be a consequence of a failure to form the correct particle. To avoid degradation, apoB100 needs to form pre-VLDL during translation and the pre-VLDL must be converted to VLDL2 (see above: The primordial lipoprotein). Both steps are dependent on the amount of lipids that are loaded on to apoB. The formation of VLDL1 is not necessary for apoB100 secretion but allows increased secretion of triglycerides from the liver.

2.4 The turnover of VLDL in the circulation

Lipid changes in metabolic diseases such as insulin resistance, the metabolic syndrome and type 2 diabetes, commonly known as diabetic dyslipidemia, consist of elevated triglycerides,

low HDL cholesterol and formation of small dense LDL. The formation of small dense LDL may occur without an increase in total LDL cholesterol, but is often connected to an increase in total apoB100.

The secreted apoB100 lipoproteins are hydrolyzed in the circulation. Because protein has a higher density than lipids, removal of the core lipids will result in the formation of smaller and denser particles. In a sequential order, hydrolysis of VLDL1 will result in first VLDL2, then intermediate-density lipoprotein (IDL) and finally LDL. The initial steps are carried out by lipoprotein lipase (LPL), which is present at the luminal side of endothelial cells in peripheral tissues such as adipose tissue, skeletal muscle and the heart. The liberated fatty acids are then taken up by different mechanisms in the target tissue (including the CD36 receptor-mediated pathway), and are re-esterified for storage or used as energy through mitochondrial oxidation. LPL has several modulators in the circulation, such as apoC-II and apoC-III, which enhance and inhibit lipolysis, respectively. New evidence also suggests that apoA-V, angiopoietin-like proteins 3 and 4, lipase maturation factor 1 and glycosylphosphatidylinositol-anchored HDL binding protein 1 (GPIHBP1) may be important for LPL function (Dallinga-Thie et al., 2010). The later steps in the removal of triglycerides are carried out by hepatic lipase. Of importance for the formation of the end product i.e. LDL is also the cholesterol ester transfer protein (CETP) (Chapman et al., 2010). IDL and LDL are removed from the circulation by the LDL receptor uptake or heparin sulphate proteoglycan mechanisms in the liver.

The triglyceride content of circulating VLDL1 has been estimated to be ~10500 molecules per particle (i.e. per apoB100 molecule), whereas VLDL2, IDL and LDL have ~3500, ~1200 and ~180-280 molecules per particle (Kumpula et al., 2008). Thus, although only 10% of the total apoB100 are in the VLDL1 and VLDL2 fractions, the majority of triglycerides are in the VLDL1 fraction and, to a lesser extent, the VLDL2 fraction (Hiukka et al., 2005). The cholesteryl ester content of lipoprotein particles increases with increasing density: VLDL1, VLDL2, IDL and LDL have ~500, ~950, ~1400 and ~1000-1500 molecules of cholesterol ester per particle (Kumpula et al., 2008). This compositional change reflects the action of cholesterol ester transfer protein, which transports cholesterol esters from HDL and LDL to VLDL particles in exchange for triglycerides (Chapman et al., 2010). This transport is increased when triglyceride levels are increased and thus type 2 diabetic subjects have lower relative amount of triglycerides in VLDL1 but higher relative amount of cholesterol esters in VLDL1 and VLDL2 compared with control subjects (Hiukka et al., 2005).

2.5 *In vivo* studies of VLDL secretion and turnover in humans

Circulating levels of apoB100, triglycerides and cholesterol are thus dependent on many different mechanisms: the rate of secretion of apoB100 and triglycerides as VLDL1 and VLDL2 particles, the rate of lipolysis by LPL and hepatic lipases (and the impact of regulating molecules on these enzymes) and the rate of removal from the circulation by uptake mechanisms. To fully understand the contribution of these mechanisms to the final plasma concentration, in particular how these different processes contribute to the development of dyslipidemia, it is necessary to quantify these within humans.

Today, most studies indirectly calculate the rates of these processes using stable isotope labeling techniques, either by *in vivo* labeling of protein content using labeled amino acids as precursors or labeling of triglycerides using labeled glycerol as precursor or by *ex vivo*

labeling (Magkos and Sidossis, 2004). The methods differ in the choice of molecules to study (i.e. triglcyerides or apoB100) and consequently in the choice of tracer molecules, but also in the choice of detail (i.e. VLDL, VLDL1 and VLDL2, or VLDL, IDL and LDL) and in the modeling approach.

Our approach is a combined experiment where the kinetics of both apoB100 and triglycerides are determined in VLDL1 and VLDL2 using a combined model (Adiels et al., 2005b). Briefly, stable isotope labeled leucine and glycerol are simultaneously injected as a bolus and blood is drawn repeatedly for 10 hours. Enrichment of leucine is measured free in plasma as well as in apoB100 protein from VLDL1 and VLDL2 particles separated by ultracentrifugation. Enrichment of glycerol is measured in the triglyceride content of the VLDL1 and VLDL2 particles. Enrichment is measured using sensitive gas-chromatograph/mass-spectrometry equipment. The time series data are used as input in a mathematical model in which the different rates of transfer and synthesis can be calculated.

The kinetics of apoB100 and triglycerides have been well studied in type 2 diabetes. Most studies have revealed an increased secretion of VLDL (Cummings et al., 1995; Kissebah et al., 1982; Ouguerram et al., 2003; Sorensen et al., 2011)) and VLDL1 (Adiels et al., 2005a; Taskinen et al., 1990). Several studies have also shown impaired suppression of VLDL secretion by insulin in type 2 diabetes (Adiels et al., 2007; Lewis et al., 1993; Malmstrom et al., 1997; Sorensen et al., 2011). Some studies also suggest that diabetic subjects have slower clearance of VLDL particles (Duvillard et al., 2000; Kissebah et al., 1982; Taskinen et al., 1986) but these results are less conclusive, which may reflect the importance of other factors such as genetic background and the progress of diabetes.

3. Acknowledgement

This work was supported by grants from the Swedish Research Council, the Swedish Foundation for Strategic Research, the Swedish Heart and Lung Foundation, Söderbergs Foundation, the Swedish Diabetes association, and the EU projects LipidomicNet. .

4. References

Adiels, M., J. Boren, M.J. Caslake, P. Stewart, A. Soro, J. Westerbacka, B. Wennberg, S.O. Olofsson, C. Packard, and M.R. Taskinen. 2005a. Overproduction of VLDL1 driven by hyperglycemia is a dominant feature of diabetic dyslipidemia. *Arterioscler Thromb Vasc Biol*. 25:1697-1703.

Adiels, M., C. Packard, M.J. Caslake, P. Stewart, A. Soro, J. Westerbacka, B. Wennberg, S.O. Olofsson, M.R. Taskinen, and J. Boren. 2005b. A new combined multicompartmental model for apolipoprotein B-100 and triglyceride metabolism in VLDL subfractions. *J Lipid Res*. 46:58-67.

Adiels, M., M.R. Taskinen, C. Packard, M.J. Caslake, A. Soro-Paavonen, J. Westerbacka, S. Vehkavaara, A. Hakkinen, S.O. Olofsson, H. Yki-Jarvinen, and J. Boren. 2006. Overproduction of large VLDL particles is driven by increased liver fat content in man. *Diabetologia*. 49:755-765.

Adiels, M., J. Westerbacka, A. Soro-Paavonen, A.M. Hakkinen, S. Vehkavaara, M.J. Caslake, C. Packard, S.O. Olofsson, H. Yki-Jarvinen, M.R. Taskinen, and J. Boren. 2007.

Acute suppression of VLDL1 secretion rate by insulin is associated with hepatic fat content and insulin resistance. *Diabetologia*. 50:2356-2365.

Alexander, C.A., R.L. Hamilton, and R.J. Havel. 1976. Subcellular localization of B apoprotein of plasma lipoproteins in rat liver. *J. Cell Biol.* 69:241–263.

Andersson, L., P. Bostrom, J. Ericson, M. Rutberg, B. Magnusson, D. Marchesan, M. Ruiz, L. Asp, P. Huang, M.A. Frohman, J. Boren, and S.O. Olofsson. 2006. PLD1 and ERK2 regulate cytosolic lipid droplet formation. *J. Cell. Sci.* 119:2246-2257.

Asp, L., C. Claesson, J. Borén, and S.-O. Olofsson. 2000. ADP-ribosylation factor 1 and its activation of phospholipase D are important for the assembly of very low density lipoproteins. *J. Biol. Chem.* 275:26285 - 26292.

Binns, D., T. Januszewski, Y. Chen, J. Hill, V.S. Markin, Y. Zhao, C. Gilpin, K.D. Chapman, R.G. Anderson, and J.M. Goodman. 2006. An intimate collaboration between peroxisomes and lipid bodies. *J Cell Biol*. 173:719-731.

Bjornheden, T., M. Levin, M. Evaldsson, and O. Wiklund. 1999. Evidence of hypoxic areas within the arterial wall in vivo. *Arterioscler Thromb Vasc Biol*. 19:870-876.

Borén, J., S. Rustaeus, M. Wettesten, M. Andersson, A. Wiklund, and S.-O. Olofsson. 1993. Influence of triacylglycerol biosynthesis rate on the assembly of apoB-100–containing lipoproteins in Hep G2 cells. *Arterioscler. Thromb.* 13:1743–1754.

Bostrom, P., L. Andersson, M. Rutberg, J. Perman, U. Lidberg, B.R. Johansson, J. Fernandez-Rodriguez, J. Ericson, T. Nilsson, J. Boren, and S.O. Olofsson. 2007. SNARE proteins mediate fusion between cytosolic lipid droplets and are implicated in insulin sensitivity. *Nat Cell Biol*. 9:1286-1293.

Bostrom, P., L. Andersson, B. Vind, L. Haversen, M. Rutberg, Y. Wickstrom, E. Larsson, P.A. Jansson, M.K. Svensson, R. Branemark, C. Ling, H. Beck-Nielsen, J. Boren, K. Hojlund, and S.O. Olofsson. 2010. The SNARE protein SNAP23 and the SNARE-interacting protein Munc18c in human skeletal muscle are implicated in insulin resistance/type 2 diabetes. *Diabetes*. 59:1870-1878.

Bostrom, P., M. Rutberg, J. Ericsson, P. Holmdahl, L. Andersson, M.A. Frohman, J. Boren, and S.O. Olofsson. 2005. Cytosolic lipid droplets increase in size by microtubule-dependent complex formation. *Arterioscler Thromb Vasc Biol*. 25:1945-1951.

Boström, K., J. Borén, M. Wettesten, A. Sjöberg, G. Bondjers, O. Wiklund, P. Carlsson, and S.-O. Olofsson. 1988. Studies on the assembly of apo B-100-containing lipoproteins in HepG2 cells. *J. Biol. Chem*. 263:4434–4442.

Boström, K., M. Wettesten, J. Borén, G. Bondjers, O. Wiklund, and S.-O. Olofsson. 1986. Pulse-chase studies of the synthesis and intracellular transport of apolipoprotein B-100 in Hep G2 cells. *J. Biol. Chem*. 261:13800-13806.

Brasaemle, D.L. 2007. Thematic review series: Adipocyte Biology. The perilipin family of structural lipid droplet proteins: stabilization of lipid droplets and control of lipolysis. *J Lipid Res*. 48:2547-2559.

Brasaemle, D.L., T. Barber, N.E. Wolins, G. Serrero, E.J. Blanchette-Mackie, and C. Londos. 1997. Adipose differentiation-related protein is an ubiquitously expressed lipid storage droplet-associated protein. *J Lipid Res*. 38:2249-2263.

Brasaemle, D.L., G. Dolios, L. Shapiro, and R. Wang. 2004. Proteomic analysis of proteins associated with lipid droplets of basal and lipolytically stimulated 3T3-L1 adipocytes. *J Biol Chem*. 279:46835-46842.

Brasaemle, D.L., B. Rubin, I.A. Harten, J. Gruia-Gray, A.R. Kimmel, and C. Londos. 2000. Perilipin A increases triacylglycerol storage by decreasing the rate of triacylglycerol hydrolysis. *J Biol Chem*. 275:38486-38493.

Brown, D.A. 2001. Lipid droplets: Proteins floating on a pool of fat. *Curr Biol*. 11:R446-449.

Carroll, K.S., J. Hanna, I. Simon, J. Krise, P. Barbero, and S.R. Pfeffer. 2001. Role of Rab9 GTPase in facilitating receptor recruitment by TIP47. *Science*. 292:1373-1376.

Cermelli, S., Y. Guo, S.P. Gross, and M.A. Welte. 2006. The lipid-droplet proteome reveals that droplets are a protein-storage depot. *Curr Biol*. 16:1783-1795.

Chapman, M.J., W. Le Goff, M. Guerin, and A. Kontush. 2010. Cholesteryl ester transfer protein: at the heart of the action of lipid-modulating therapy with statins, fibrates, niacin, and cholesteryl ester transfer protein inhibitors. *Eur Heart J*. 31:149-164.

Cummings, M.H., G.F. Watts, A.M. Umpleby, T.R. Hennessy, R. Naoumova, B.M. Slavin, G.R. Thompson, and P.H. Sonksen. 1995. Increased hepatic secretion of very-low-density lipoprotein apolipoprotein B-100 in NIDDM. *Diabetologia*. 38:959-967.

Dalen, K.T., T. Dahl, E. Holter, B. Arntsen, C. Londos, C. Sztalryd, and H.I. Nebb. 2007. LSDP5 is a PAT protein specifically expressed in fatty acid oxidizing tissues. *Biochim Biophys Acta*. 1771:210-227.

Dalen, K.T., K. Schoonjans, S.M. Ulven, M.S. Weedon-Fekjaer, T.G. Bentzen, H. Koutnikova, J. Auwerx, and H.I. Nebb. 2004. Adipose tissue expression of the lipid droplet-associating proteins S3-12 and perilipin is controlled by peroxisome proliferator-activated receptor-gamma. *Diabetes*. 53:1243-1252.

Dalen, K.T., S.M. Ulven, B.M. Arntsen, K. Solaas, and H.I. Nebb. 2006. PPARalpha activators and fasting induce the expression of adipose differentiation-related protein in liver. *J Lipid Res*. 47:931-943.

Dallinga-Thie, G.M., R. Franssen, H.L. Mooij, M.E. Visser, H.C. Hassing, F. Peelman, J.J. Kastelein, M. Peterfy, and M. Nieuwdorp. 2010. The metabolism of triglyceride-rich lipoproteins revisited: new players, new insight. *Atherosclerosis*. 211:1-8.

Davidson, N.O., and G.S. Shelness. 2000. Apolipoprotein B: mRNA editing, lipoprotein assembly, and presecretory degradation. *Ann. Rev. Nutr.* 20:169-193.

Diaz, E., and S.R. Pfeffer. 1998. TIP47: a cargo selection device for mannose 6-phosphate receptor trafficking. *Cell*. 93:433-443.

Dolinsky, V.W., D.N. Douglas, R. Lehner, and D.E. Vance. 2004a. Regulation of the enzymes of hepatic microsomal triacylglycerol lipolysis and re-esterification by the glucocorticoid dexamethasone. *Biochem J*. 378:967-974.

Dolinsky, V.W., D. Gilham, M. Alam, D.E. Vance, and R. Lehner. 2004b. Triacylglycerol hydrolase: role in intracellular lipid metabolism. *Cell Mol Life Sci*. 61:1633-1651.

Donath, M.Y., and S.E. Shoelson. 2011. Type 2 diabetes as an inflammatory disease. *Nat Rev Immunol*. 11:98-107.

Duvillard, L., F. Pont, E. Florentin, C. Galland-Jos, P. Gambert, and B. Verges. 2000. Metabolic abnormalities of apolipoprotein B-containing lipoproteins in non-insulin-dependent diabetes: a stable isotope kinetic study. *Eur J Clin Invest*. 30:685-694.

Edvardsson, U., A. Ljungberg, D. Linden, L. William-Olsson, H. Peilot-Sjogren, A. Ahnmark, and J. Oscarsson. 2006. PPARalpha activation increases triglyceride mass and adipose differentiation-related protein in hepatocytes. *J Lipid Res*. 47:329-340.

Ellgaard, L., and A. Helenius. 2001. ER quality control: towards an understanding at the molecular level. *Curr Opin Cell Biol*. 13:431-437.

Ellgaard, L., and A. Helenius. 2003. Quality control in the endoplasmic reticulum. *Nat Rev Mol Cell Biol*. 4:181-191.

Ellgaard, L., M. Molinari, and A. Helenius. 1999. Setting the standards:Quality control in the secretory pathway. *Science*. 286:1882 - 1888.

Elsner, M., H. Hashimoto, and T. Nilsson. 2003. Cisternal maturation and vesicle transport: join the band wagon! (Review). *Mol Membr Biol*. 20:221-229.

Fabbrini, E., F. Magkos, B.S. Mohammed, T. Pietka, N.A. Abumrad, B.W. Patterson, A. Okunade, and S. Klein. 2009. Intrahepatic fat, not visceral fat, is linked with metabolic complications of obesity. *Proc Natl Acad Sci U S A*. 106:15430-15435.

Fabbrini, E., B.S. Mohammed, F. Magkos, K.M. Korenblat, B.W. Patterson, and S. Klein. 2008. Alterations in adipose tissue and hepatic lipid kinetics in obese men and women with nonalcoholic fatty liver disease. *Gastroenterology*. 134:424-431.

Fisher, E.A., and H.N. Ginsberg. 2002. Complexity in the secretory pathway: the assembly and secretion of apolipoprotein B-containing lipoproteins. *J Biol Chem*. 277:17377-17380.

Fisher, E.A., M. Pan, X. Chen, X. Wu, H. Wang, H. Jamil, J.D. Sparks, and K.J. Williams. 2001. The triple threat to nascent apolipoprotein B. Evidence for multiple, distinct degradative pathways. *J Biol Chem*. 276:27855-27863.

Franke, W.W., M. Hergt, and C. Grund. 1987. Rearragement of vimentin cytoskeleton durin adipose conversion: formation of an intermediate filament cage around lipid globules. *Cell*. 49:131-141.

Gibbons, G.F., K. Islam, and R.J. Pease. 2000. Mobilisation of triacylglycerol stores. *Biochim. Biophys. Acta*. 1483:37-57.

Gilham, D., S. Ho, M. Rasouli, P. Martres, D.E. Vance, and R. Lehner. 2003. Inhibitors of hepatic microsomal triacylglycerol hydrolase decrease very low density lipoprotein secretion. *Faseb J*. 17:1685-1687.

Giraudo, C.G., A. Garcia-Diaz, W.S. Eng, Y. Chen, W.A. Hendrickson, T.J. Melia, and J.E. Rothman. 2009. Alternative zippering as an on-off switch for SNARE-mediated fusion. *Science*. 323:512-516.

Goodpaster, B.H., J. He, S. Watkins, and D.E. Kelley. 2001. Skeletal muscle lipid content and insulin resistance: evidence for a paradox in endurance-trained athletes. *J Clin Endocrinol Metab*. 86:5755-5761.

Granneman, J.G., H.P. Moore, R.L. Granneman, A.S. Greenberg, M.S. Obin, and Z. Zhu. 2007. Analysis of lipolytic protein trafficking and interactions in adipocytes. *J Biol Chem*. 282:5726-5735.

Greaves, D.R., and S. Gordon. 2005. Thematic review series: the immune system and atherogenesis. Recent insights into the biology of macrophage scavenger receptors. *J Lipid Res*. 46:11-20.

Gubern, A., J. Casas, M. Barcelo-Torns, D. Barneda, X. de la Rosa, R. Masgrau, F. Picatoste, J. Balsinde, M.A. Balboa, and E. Claro. 2008. Group IVA phospholipase A2 is necessary for the biogenesis of lipid droplets. *J Biol Chem*. 283:27369-27382.

Guo, Y., T.C. Walther, M. Rao, N. Stuurman, G. Goshima, K. Terayama, J.S. Wong, R.D. Vale, P. Walter, and R.V. Farese. 2008. Functional genomic screen reveals genes involved in lipid-droplet formation and utilization. *Nature*. 453:657-661.

Heid, H.W., R. Moll, I. Schwetlick, H.R. Rackwitz, and T.W. Keenan. 1998. Adipophilin is a specific marker of lipid accumulation in diverse cell types and diseases. *Cell Tissue Res*. 294:309-321.

Hiukka, A., J. Fruchart-Najib, E. Leinonen, H. Hilden, J.C. Fruchart, and M.R. Taskinen. 2005. Alterations of lipids and apolipoprotein CIII in very low density lipoprotein subspecies in type 2 diabetes. *Diabetologia*. 48:1207-1215.

Hommel, A., D. Hesse, W. Volker, A. Jaschke, M. Moser, T. Engel, M. Bluher, C. Zahn, A. Chadt, K. Ruschke, H. Vogel, R. Kluge, H. Robenek, H.G. Joost, and A. Schurmann. 2010. The ARF-like GTPase ARFRP1 is essential for lipid droplet growth and is involved in the regulation of lipolysis. *Mol Cell Biol*. 30:1231-1242.

Hong, W. 2005. SNAREs and traffic. *Biochim Biophys Acta*. 1744:493-517.

Horton, J.D., H. Shimano, R.L. Hamilton, M.S. Brown, and J.L. Goldstein. 1999. Disruption of LDL receptor gene in transgenic SREBP-1a mice unmask hyperlipidemia resulting from production of lipid-rich VLDL. *J.Clin.Invest.* 103:1067-1076.

Imamura, M., T. Inoguchi, S. Ikuyama, S. Taniguchi, K. Kobayashi, N. Nakashima, and H. Nawata. 2002. ADRP stimulates lipid accumulation and lipid droplet formation in murine fibroblasts. *Am J Physiol Endocrinol Metab*. 283:E775-783.

Jahn, R., and R.H. Scheller. 2006. SNAREs--engines for membrane fusion. *Nat Rev Mol Cell Biol*. 7:631-643.

Johnson, A.E., and N.G. Haigh. 2000. The ER translocon and retrotranslocation: is the shift into reverse manual or automatic? *Cell*. 102:709-712.

Johnson, A.E., and M.A. van Waes. 1999. The translocon: a dynamic gateway at the ER membrane. *Annu Rev Cell Dev Biol*. 15:799-842.

Kartberg, F., M. Elsner, L. Froderberg, L. Asp, and T. Nilsson. 2005. Commuting between Golgi cisternae-mind the GAP! *Biochim Biophys Acta*.

Kissebah, A.H., S. Alfarsi, D.J. Evans, and P.W. Adams. 1982. Integrated regulation of very low density lipoprotein triglyceride and apolipoprotein-B kinetics in non-insulin-dependent diabetes mellitus. *Diabetes*. 31:217-225.

Koliwad, S.K., R.S. Streeper, M. Monetti, I. Cornelissen, L. Chan, K. Terayama, S. Naylor, M. Rao, B. Hubbard, and R.V. Farese, Jr. 2010. DGAT1-dependent triacylglycerol storage by macrophages protects mice from diet-induced insulin resistance and inflammation. *J Clin Invest*. 120:756-767.

Kostova, Z., and D.H. Wolf. 2003. For whom the bell tolls: protein quality control of the endoplasmic reticulum and the ubiquitin-proteasome connection. *Embo J*. 22:2309-2317.

Koves, T.R., J.R. Ussher, R.C. Noland, D. Slentz, M. Mosedale, O. Ilkayeva, J. Bain, R. Stevens, J.R. Dyck, C.B. Newgard, G.D. Lopaschuk, and D.M. Muoio. 2008. Mitochondrial overload and incomplete Fatty Acid oxidation contribute to skeletal muscle insulin resistance. *Cell Metab*. 7:45-56.

Krise, J.P., P.M. Sincock, J.G. Orsel, and S.R. Pfeffer. 2000. Quantitative analysis of TIP47-receptor cytoplasmic domain interactions: implications for endosome-to-trans Golgi network trafficking. *J Biol Chem*. 275:25188-25193.

Kuerschner, L., C. Moessinger, and C. Thiele. 2008. Imaging of lipid biosynthesis: how a neutral lipid enters lipid droplets. *Traffic*. 9:338-352.

Kumpula, L.S., J.M. Kumpula, M.R. Taskinen, M. Jauhiainen, K. Kaski, and M. Ala-Korpela. 2008. Reconsideration of hydrophobic lipid distributions in lipoprotein particles. *Chem Phys Lipids*. 155:57-62.

Lass, A., R. Zimmermann, G. Haemmerle, M. Riederer, G. Schoiswohl, M. Schweiger, P. Kienesberger, J.G. Strauss, G. Gorkiewicz, and R. Zechner. 2006. Adipose triglyceride lipase-mediated lipolysis of cellular fat stores is activated by CGI-58 and defective in Chanarin-Dorfman Syndrome. *Cell Metab*. 3:309-319.

Lehner, R., and D.E. Vance. 1999. Cloning and expression of a cDNA encoding a hepatic microsomal lipase that mobilizes stored triacylglycerol. *Biochem J*. 343 Pt 1:1-10.

Lewis, G.F., K.D. Uffelman, L.W. Szeto, and G. Steiner. 1993. Effects of acute hyperinsulinemia on VLDL triglyceride and VLDL apoB production in normal weight and obese individuals. *Diabetes*. 42:833-842.

Li, L., P. Stillemark-Billton, C. Beck, P. Bostrom, L. Andersson, M. Rutberg, J. Ericsson, B. Magnusson, D. Marchesan, A. Ljungberg, J. Boren, and S.O. Olofsson. 2005. Epigallocatechin gallate promotes the formation of cytosolic lipid droplets and causes a subsequent reduction in the assembly and secretion of VLDL-containing apoB-100. *J Lipid Res*.

Liang, J.-S., X. Wu, E.A. Fisher, and H.N. Ginsberg. 2000. The amino-terminal domain of apolipoprotein B does not undergo retrograde translocation from the endoplasmic reticulum to the cytosol. Proteasomal degradation of nascent apolipoprotein B begins at the carboxyl terminus of the protein, while apolipoprotein B is still in its original translocon. *J. Biol. Chem.* 275:32003-32010.

Lippincott-Schwartz, J., T.H. Roberts, and K. Hirschberg. 2000. Secretory protein trafficking and organelle dynamics in living cells. *Annu Rev Cell Dev Biol*. 16:557-589.

Liu, P., Y. Ying, Y. Zhao, D.I. Mundy, M. Zhu, and R.G. Anderson. 2004. Chinese hamster ovary K2 cell lipid droplets appear to be metabolic organelles involved in membrane traffic. *J Biol Chem*. 279:3787-3792.

Londos, C., D.L. Brasaemle, J. Gruia-Gray, D.A. Servetnick, C.J. Schultz, D.M. Levin, and A.R. Kimmel. 1995. Perilipin: unique proteins associated with intracellular neutral lipid droplets in adipocytes and steroidogenic cells. *Biochem Soc Trans*. 23:611-615.

Londos, C., D.L. Brasaemle, C.J. Schultz, J.P. Segrest, and A.R. Kimmel. 1999. Perilipins, ADRP, and other proteins that associate with intracellular neutral lipid droplets in animal cells. *Semin Cell Dev Biol*. 10:51-58.

Londos, C., C. Sztalryd, J.T. Tansey, and A.R. Kimmel. 2005. Role of PAT proteins in lipid metabolism. *Biochimie*. 87:45-49.

Lu, X., J. Gruia-Gray, N.G. Copeland, D.J. Gilbert, N.A. Jenkins, C. Londos, and A.R. Kimmel. 2001. The murine perilipin gene: the lipid droplet-associated perilipins derive from tissue-specific, mRNA splice variants and define a gene family of ancient origin. *Mamm Genome*. 12:741-749.

Magkos, F., and L.S. Sidossis. 2004. Measuring very low density lipoprotein-triglyceride kinetics in man in vivo: how different the various methods really are. *Curr Opin Clin Nutr Metab Care*. 7:547-555.

Magnusson, B., L. Asp, P. Bostrom, M. Ruiz, P. Stillemark-Billton, D. Linden, J. Boren, and S.O. Olofsson. 2006. Adipocyte differentiation-related protein promotes fatty acid storage in cytosolic triglycerides and inhibits secretion of very low-density lipoproteins. *Arterioscler Thromb Vasc Biol*. 26:1566-1571.

Malmstrom, R., C.J. Packard, M. Caslake, D. Bedford, P. Stewart, H. Yki-Jarvinen, J. Shepherd, and M.R. Taskinen. 1997. Defective regulation of triglyceride metabolism by insulin in the liver in NIDDM. *Diabetologia*. 40:454-462.

Malsam, J., S. Kreye, and T.H. Sollner. 2008. Membrane fusion: SNAREs and regulation. *Cell Mol Life Sci*. 65:2814-2832.

Marchesan, D., M. Rutberg, L. Andersson, L. Asp, T. Larsson, J. Boren, B.R. Johansson, and S.O. Olofsson. 2003. A phospholipase D-dependent process forms lipid droplets containing caveolin, adipocyte differentiation-related protein, and vimentin in a cell-free system. *J Biol Chem*. 278:27293-27300.

Martin, S., and R.G. Parton. 2006. Lipid droplets: a unified view of a dynamic organelle. *Nat Rev Mol Cell Biol*. 7:373-378.

Martinez-Botas, J., J.B. Anderson, D. Tessier, A. Lapillonne, B.H. Chang, M.J. Quast, D. Gorenstein, K.H. Chen, and L. Chan. 2000. Absence of perilipin results in leanness and reverses obesity in Lepr(db/db) mice. *Nat Genet*. 26:474-479.

Masuda, Y., H. Itabe, M. Odaki, K. Hama, Y. Fujimoto, M. Mori, N. Sasabe, J. Aoki, H. Arai, and T. Takano. 2006. ADRP/adipophilin is degraded through the proteasome-dependent pathway during regression of lipid-storing cells. *J Lipid Res*. 47:87-98.

Mattsson, L., H. Johansson, M. Ottoson, G. Bondjers, and O. Wiklund. 1993. Expression of lipoprotein lipase mRNA and secretion in macrophages isolated from human atherosclerotic aorta. *J. Clin. Invest.* 92:1759-1765.

McDermott, M., M.J. Wakelam, and A.J. Morris. 2004. Phospholipase D. *Biochem Cell Biol*. 82:225-253.

Mitchell, D.M., M. Zhou, R. Pariyarath, H. Wang, J.D. Aitchison, H.N. Ginsberg, and E.A. Fisher. 1998. Apoprotein B 100 har a prolonged interaction with the translocon during which its lipidation and translocation change from dependence on the microsomal triglyceride transfer protein to independence. *Proc.Natl. Acad. Sci.USA*. 95:14733 - 14738.

Miyoshi, H., J.W. Perfield, 2nd, S.C. Souza, W.J. Shen, H.H. Zhang, Z.S. Stancheva, F.B. Kraemer, M.S. Obin, and A.S. Greenberg. 2007. Control of adipose triglyceride lipase action by serine 517 of perilipin A globally regulates protein kinase A-stimulated lipolysis in adipocytes. *J Biol Chem*. 282:996-1002.

Murphy, D.J., and J. Vance. 1999. Mechanisms of lipid-body formation. *Trends Biochem Sci*. 24:109-115.

Olofsson, S.-O., and L. Asp. 2005. The assembly of Very Low density lipoproteins (VLDL) in the liver. *in Packard CJ and Rader D (eds) Lipid and Atherosclerosis: Advances in translational medicine*. London UK: Taylor and Francis:1-15.

Olofsson, S.-O., L. Asp, and J. Borén. 1999. The assembly and secretion of apolipoprotein B-containing lipoproteins. *Curr. Opin. Lipidol.* 10:341 - 346.

Olofsson, S.-O., G. Bjursell, K. Boström, P. Carlsson, J. Elovson, A.A. Protter, M.A. Reuben, and G. Bondjers. 1987. Apolipoprotein B: Structure, biosynthesis and role in the lipoprotein assembly process. *Atherosclerosis*. 68:1–17.

Olofsson, S.-O., P. Stillemark-Billton, and L. Asp. 2000. The intracellular assembly of VLDL-a process that consists of two major steps that occur in separate cell compartments. *Trends. Cardiovasc. Med.* 10:338 - 345.

Olofsson, S.O., P. Bostrom, L. Andersson, M. Rutberg, M. Levin, J. Perman, and J. Boren. 2008. Triglyceride containing lipid droplets and lipid droplet-associated proteins. *Curr Opin Lipidol*. 19:441-447.

Olofsson, S.O., P. Bostrom, L. Andersson, M. Rutberg, J. Perman, and J. Boren. 2009. Lipid droplets as dynamic organelles connecting storage and efflux of lipids. *Biochim Biophys Acta*. 1791:448-458.

Ost, A., U. Ortegren, J. Gustavsson, F.H. Nystrom, and P. Stralfors. 2005. Triacylglycerol is synthesized in a specific subclass of caveolae in primary adipocytes. *J Biol Chem*. 280:5-8.

Ouguerram, K., T. Magot, Y. Zair, J.S. Marchini, B. Charbonnel, H. Laouenan, and M. Krempf. 2003. Effect of atorvastatin on apolipoprotein B100 containing lipoprotein metabolism in type-2 diabetes. *J Pharmacol Exp Ther*. 306:332-337.

Ozeki, S., J. Cheng, K. Tauchi-Sato, N. Hatano, H. Taniguchi, and T. Fujimoto. 2005. Rab18 localizes to lipid droplets and induces their close apposition to the endoplasmic reticulum-derived membrane. *J Cell Sci*. 118:2601-2611.

Pan, M., V. Maitin, S. Parathath, U. Andreo, S.X. Lin, C. St Germain, Z. Yao, F.R. Maxfield, K.J. Williams, and E.A. Fisher. 2008. Presecretory oxidation, aggregation, and autophagic destruction of apoprotein-B: a pathway for late-stage quality control. *Proc Natl Acad Sci U S A*. 105:5862-5867.

Pariyarath, R., H. Wang, J.D. Aitchison, H.N. Ginsberg, W.J. Welch, A.E. Johnson, and E.A. Fisher. 2001. Co-translational interactions of apoprotein B with the ribosome and translocon during lipoprotein assembly or targeting to the proteasome. *J Biol Chem*. 276:541-550.

Perman, J.C., P. Bostrom, M. Lindbom, U. Lidberg, M. Stahlman, D. Hagg, H. Lindskog, M. Scharin Tang, E. Omerovic, L. Mattsson Hulten, A. Jeppsson, P. Petursson, J. Herlitz, G. Olivecrona, D.K. Strickland, K. Ekroos, S.O. Olofsson, and J. Boren. 2011. The VLDL receptor promotes lipotoxicity and increases mortality in mice following an acute myocardial infarction. *J Clin Invest*. 121:2625-2640.

Powner, D.J., and M.J. Wakelam. 2002. The regulation of phospholipase D by inositol phospholipids and small GTPases. *FEBS Lett*. 531:62-64.

Salter, A.M., D. Wiggins, V.A. Sessions, and G.F. Gibbons. 1998. The intracellular triacylglycerol/fatty acid cycle: a comparison of its activity in hepatocytes which secrete exclusively apolipoprotein (apo) B100 very-low-density lipoprotein (VLDL) and in those which secrete predominantly apoB48 VLDL. *Biochem J*. 332 (Pt 3):667-672.

Samuel, V.T., K.F. Petersen, and G.I. Shulman. 2010. Lipid-induced insulin resistance: unravelling the mechanism. *Lancet*. 375:2267-2277.

Shaw, C.S., D.A. Jones, and A.J. Wagenmakers. 2008. Network distribution of mitochondria and lipid droplets in human muscle fibres. *Histochem Cell Biol*. 129:65-72.

Shelness, G.S., and J.A. Sellers. 2001. Very-low-density lipoprotein assembly and secretion. *Curr Opin Lipidol*. 12:151-157.

Sorensen, L.P., I.R. Andersen, E. Sondergaard, L.C. Gormsen, O. Schmitz, J.S. Christiansen, and S. Nielsen. 2011. Basal and insulin mediated VLDL-triglyceride kinetics in type 2 diabetic men. *Diabetes*. 60:88-96.

Stillemark-Billton, P., C. Beck, J. Boren, and S.O. Olofsson. 2005. Relation of the size and intracellular sorting of apoB to the formation of VLDL 1 and VLDL 2. *J Lipid Res*. 46:104-114.

Stillemark, P., J. Borén, M. Andersson, T. Larsson, S. Rustaeus, K.-A. Karlsson, and S.-O. Olofsson. 2000. The assembly and secretion of apolipoprotein-B48-containing very low density lipoproteins in McA-RH7777 cells. *J.Biol.Chem.* 275:10506 - 10513.

Stone, S.J., M.C. Levin, and R.V. Farese, Jr. 2006. Membrane topology and identification of key functional amino acid residues of murine acyl-CoA:diacylglycerol acyltransferase-2. *J Biol Chem*. 281:40273-40282.

Stone, S.J., M.C. Levin, P. Zhou, J. Han, T.C. Walther, and R.V. Farese, Jr. 2009. The endoplasmic reticulum enzyme DGAT2 is found in mitochondria-associated membranes and has a mitochondrial targeting signal that promotes its association with mitochondria. *J Biol Chem*. 284:5352-5361.

Sudhof, T.C., and J.E. Rothman. 2009. Membrane fusion: grappling with SNARE and SM proteins. *Science*. 323:474-477.

Summers, S.A. 2006. Ceramides in insulin resistance and lipotoxicity. *Prog Lipid Res*. 45:42-72.

Tansey, J.T., C. Sztalryd, J. Gruia-Gray, D.L. Roush, J.V. Zee, O. Gavrilova, M.L. Reitman, C.X. Deng, C. Li, A.R. Kimmel, and C. Londos. 2001. Perilipin ablation results in a lean mouse with aberrant adipocyte lipolysis, enhanced leptin production, and resistance to diet-induced obesity. *Proc Natl Acad Sci U S A*. 98:6494-6499.

Targett-Adams, P., D. Chambers, S. Gledhill, R.G. Hope, J.F. Coy, A. Girod, and J. McLauchlan. 2003. Live cell analysis and targeting of the lipid droplet-binding adipocyte differentiation-related protein. *J Biol Chem*. 278:15998-16007.

Taskinen, M.R. 2003. Diabetic dyslipidaemia: from basic research to clinical practice. *Diabetologia*. 46:733-749.

Taskinen, M.R., W.F. Beltz, I. Harper, R.M. Fields, G. Schonfeld, S.M. Grundy, and B.V. Howard. 1986. Effects of NIDDM on very-low-density lipoprotein triglyceride and apolipoprotein B metabolism. Studies before and after sulfonylurea therapy. *Diabetes*. 35:1268-1277.

Taskinen, M.R., C.J. Packard, and J. Shepherd. 1990. Effect of insulin therapy on metabolic fate of apolipoprotein B-containing lipoproteins in NIDDM. *Diabetes*. 39:1017-1027.

Trayhurn, P., B. Wang, and I.S. Wood. 2008. Hypoxia in adipose tissue: a basis for the dysregulation of tissue function in obesity? *Br J Nutr*. 100:227-235.

Trickett, J.I., D.D. Patel, B.L. Knight, E.D. Saggerson, G.F. Gibbons, and R.J. Pease. 2001. Characterization of the rodent genes for arylacetamide deacetylase, a putative microsomal lipase, and evidence for transcriptional regulation. *J Biol Chem*. 276:39522-39532.

Twisk, J., D.L. Gillian-Daniel, A. Tebon, L. Wang, P.H. Barrett, and A.D. Attie. 2000. The role of the LDL receptor in apolipoprotein B secretion. *J. Clin. Invest.* 105:521 - 532.

van Loon, L.J., and B.H. Goodpaster. 2006. Increased intramuscular lipid storage in the insulin-resistant and endurance-trained state. *Pflugers Arch*. 451:606-616.

Wang, S.M., R.D. Hwang, A.S. Greenberg, and H.L. Yeo. 2003. Temporal and spatial assembly of lipid droplet-associated proteins in 3T3-L1 preadipocytes. *Histochem Cell Biol*. 120:285-292.

Welte, M.A., S.P. Gross, M. Postner, S.M. Block, and E.F. Wieschaus. 1998. Developmental regulation of vesicle transport in Drosophila embryos: forces and kinetics. *Cell*. 92:547-557.

Wiggins, D., and G.F. Gibbons. 1992. The lipolysis/esterification cycle of hepatic triacylglycerol. Its role in the secretion of very-low-density lipoprotein and its response to hormones and sulphonylureas. *Biochem. J.* 284:457–462.

Williams, K.J., R.W. Brocia, and E.A. Fisher. 1990. The unstirred water layer as a site of control of apolipoprotein B secretion. *J. Biol. Chem*. 265:16741-16744.

Wolins, N.E., B.K. Quaynor, J.R. Skinner, A. Tzekov, M.A. Croce, M.C. Gropler, V. Varma, A. Yao-Borengasser, N. Rasouli, P.A. Kern, B.N. Finck, and P.E. Bickel. 2006. OXPAT/PAT-1 is a PPAR-induced lipid droplet protein that promotes fatty acid utilization. *Diabetes*. 55:3418-3428.

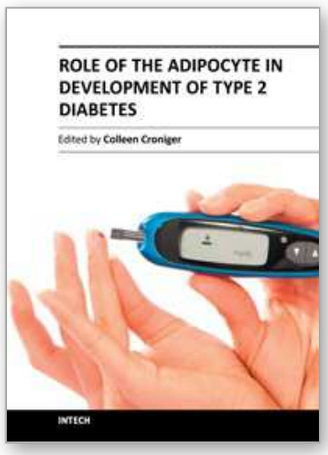
Wolins, N.E., B. Rubin, and D.L. Brasaemle. 2001. TIP47 associates with lipid droplets. *J Biol Chem*. 276:5101-5108.

Wolins, N.E., J.R. Skinner, M.J. Schoenfish, A. Tzekov, K.G. Bensch, and P.E. Bickel. 2003. Adipocyte protein S3-12 coats nascent lipid droplets. *J Biol Chem*. 278:37713-37721.

Xu, G., C. Sztalryd, X. Lu, J.T. Tansey, J. Gan, H. Dorward, A.R. Kimmel, and C. Londos. 2005. Post-translational regulation of adipose differentiation-related protein by the ubiquitin/proteasome pathway. *J Biol Chem*. 280:42841-42847.

Yamaguchi, T., S. Matsushita, K. Motojima, F. Hirose, and T. Osumi. 2006. MLDP, a novel PAT family protein localized to lipid droplets and enriched in the heart, is regulated by peroxisome proliferator-activated receptor alpha. *J Biol Chem*. 281:14232-14240.

Ye, J. 2009. Emerging role of adipose tissue hypoxia in obesity and insulin resistance. *Int J Obes (Lond)*. 33:54-66.



Role of the Adipocyte in Development of Type 2 Diabetes

Edited by Dr. Colleen Croniger

ISBN 978-953-307-598-3
Hard cover, 372 pages
Publisher InTech
Published online 22, September, 2011
Published in print edition September, 2011

Adipocytes are important in the body for maintaining proper energy balance by storing excess energy as triglycerides. However, efforts of the last decade have identified several molecules that are secreted from adipocytes, such as leptin, which are involved in signaling between tissues and organs. These adipokines are important in overall regulation of energy metabolism and can regulate body composition as well as glucose homeostasis. Excess lipid storage in tissues other than adipose can result in development of diabetes and nonalcoholic fatty liver disease (NAFLD). In this book we review the role of adipocytes in development of insulin resistance, type 2 diabetes and NAFLD. Because type 2 diabetes has been suggested to be a disease of inflammation we included several chapters on the mechanism of inflammation modulating organ injury. Finally, we conclude with a review on exercise and nutrient regulation for the treatment of type 2 diabetes and its co-morbidities.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Sven-Olof Olofsson, Linda Andersson, Jeanna Perman, Mikael Rutberg, Lilliana Håversen, Li Lu, Emma Lu, Reza Mobini, Marcus Ståhlman, Susanna Myhre, Christina Olsson, Rosie Perkins,Thomas Larsson, Jan Borén and Martin Adiels (2011). Lipid Droplets and Very Low Density Lipoproteins; Their Relation to Insulin Resistance, Role of the Adipocyte in Development of Type 2 Diabetes, Dr. Colleen Croniger (Ed.), ISBN: 978-953-307-598-3, InTech, Available from: http://www.intechopen.com/books/role-of-the-adipocyte-in-development-of-type-2-diabetes/lipid-droplets-and-very-low-density-lipoproteins-their-relation-to-insulin-resistance

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

IntechOpen