Video Article

Using Caco-2 Cells to Study Lipid Transport by the Intestine

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Abstract

Studies of dietary fat absorption are generally conducted by using an animal model equipped with a lymph cannula. Although this animal model is widely accepted as the *in vivo* model of dietary fat absorption, the surgical techniques involved are challenging and expensive. Genetic manipulation of the animal model is also costly and time consuming. The alternative *in vitro* model is arguably more affordable, timesaving, and less challenging. Importantly, the *in vitro* model allows investigators to examine the enterocytes as an isolated system, reducing the complexity inherent in the whole organism model. This paper describes how human colon carcinoma cells (Caco-2) can serve as an *in vitro* model to study the enterocyte transport of lipids, and lipid-soluble drugs and vitamins. It explains the proper maintenance of Caco-2 cells and the preparation of their lipid mixture; and it further discusses the valuable option of using the permeable membrane system. Since differentiated Caco-2 cells are polarized, the main advantage of using the permeable membrane system is that it separates the apical from the basolateral compartment. Consequently, the lipid mixture can be added to the apical compartment while the lipoproteins can be collected from the basolateral compartment. In addition, the effectiveness of the lentivirus expression system in upregulating gene expression in Caco-2 cells is discussed. Lastly, this paper describes how to confirm the successful isolation of intestinal lipoproteins by transmission electron microscopy (TEM).

Video Link

The video component of this article can be found at https://www.jove.com/video/53086/

Introduction

Studies of intestinal absorption of dietary fat, and lipid-soluble drugs and vitamins can be conducted *in vivo* by using a lymph fistula model [1–4]. However, the surgical techniques involved are not only challenging, but also costly. Although *in vivo* approaches based on fecal analysis may be utilized, they are used mainly to determine the percent uptake by the gastrointestinal tract [2,5]. The *in vitro* model described in this paper is more cost effective, and the techniques involved are arguably less challenging. Genetic modification studies are also more economical and less time-consuming when they are conducted using this *in vitro* model.

Since lipid-soluble materials that are taken up by enterocytes are packaged into lipoproteins [6,7], the effectiveness of this *in vitro* model to produce lipoproteins is crucial. The two main intestinal lipoproteins are chylomicrons and very low-density lipoproteins (VLDL). Chylomicrons, defined as lipoproteins with 80 nm or more in diameter, are produced strictly by the small intestine when lipids are abundantly present in the gastrointestinal lumen. Since they are the largest lipoproteins, chylomicrons are conceivably the most efficient lipid transporters. This *in vitro* model, which is capable of producing chylomicrons [8], can be used to study dietary fat absorption, lipid-soluble vitamin absorption by the gut, and oral lipophilic drug bioavailability. The presence of lipid-soluble molecules, vitamins, or drugs in the lipoprotein fraction is an indicator of their absorption by the small intestine. As previously discussed, this model can be used to improve oral lipophilic drug bioavailability [6].

This paper describes how Caco-2 cells should be maintained in permeable membrane or regular tissue culture dishes, how the lipid mixture for stimulating lipoprotein production should be prepared, how the lentivirus expression system can be employed to achieve effective overexpression, and how the isolated lipoproteins should be analyzed.

Protocol

1. Maintenance of the Caco-2 Cells

1. Using regular tissue culture dishes
    1. Thaw the Caco-2 cells from a frozen vial by placing the vial in a 37 °C water bath, and immediately add them to a 10 cm tissue culture dish containing 10 ml of pre-warmed growth media (15% fetal bovine serum (FBS) in Dulbecco's Modified Eagle Medium (DMEM)).

1. When the Caco-2 cells have reached 50-70% confluence, split them 1:6 by incubating the cells with 3 ml of 0.05% Trypsin / 0.53 mM ethylenediaminetetraacetic acid (EDTA) at 37 °C until they are detached (15 min). To avoid cell clumping, mix the cells several times by gentle pipetting. Add 0.5 ml of the trypsinized cells to a 10 cm tissue culture dish containing 10 ml of pre-warmed growth media.

2. Gently shake the dishes several times in a forward and backward direction followed by a leftward and rightward direction. Avoid swirling the dishes as it may result in an unequal cell dispersion.
3. Place the dishes on a flat surface in a 37 °C incubator supplied with 5% CO_2. Slanted surfaces may also result in an unequal cell dispersion.
4. Change the growth media a day after starting the incubation.
5. Monitor the cells and record the day they reach confluence. It will take about 1 week for the cells to reach confluence from the day they are split.
6. Change the growth media twice a week before the cells reach confluence. Once the cells have reached confluence, change the growth media every other day. After the cells are 7-days post-confluent, change the growth media daily.
   Note: The cells are ready for experiments when they are 13-days post-confluent (**Figure 1**). Since the cells will eventually become less effective in producing lipoproteins, use cells that are between 13 to 17-days post-confluent [8]. Go to step 3 on how to conduct the experiment.

2. Using the permeable membrane system
   1. Seed the Caco-2 cells in the permeable membrane insert as described in step 1.1.1.1. above. Avoid using cells from a frozen vial because their cell growth is normally slower (recovery period). Briefly, add 0.5 ml of the trypsinized cells to the apical chamber (upper compartment) that contains 10 ml of pre-warmed growth media. Also, add 10 ml of pre-warmed growth media to the basolateral chamber (lower compartment).
      Note: For best practice, add the growth media to the apical chamber first and then to the basolateral chamber. When removing the old media, remove the basolateral media before the apical media. Avoid poking the polycarbonate membrane as it may rupture the membrane.
   2. Due to poor cell visibility through the polycarbonate membrane, seed the Caco-2 cells in a regular tissue culture dish with similar density, and use this dish to judge the cell confluence.
   3. Follow steps 1.1.2-1.1.6 above.

2. Gene Overexpression

1. Using the regular transfection approach
   1. Seed the Caco-2 cells on a tissue culture dish as described in 1.1.1.1.-1.1.4 above.
      Note: When the cells are about 40-50% confluent, they are ready to be transfected.
   2. Add 67 µl of the transfection reagent to 472 µl of the reduced serum media in a microcentrifuge tube. Avoid contact of the undiluted transfection reagent with the tube wall.
   3. Add 23 µg of pLL3.7 enhanced green fluorescent protein (eGFP) [9] into the transfection reagent/reduced serum media mixture.
   4. Incubate the mixture for 20 min at RT.
   5. Replace the Caco-2 cells' growth media with 8 ml of 10% FBS in DMEM.
   6. Add the DNA/transfection reagent/reduced serum media mixture drop-wise to the dish.
   7. Gently shake the dishes several times in a forward and backward direction followed by a leftward and rightward direction.
   8. Place the dish in the 37 °C incubator.
   9. Replace the media in the dish with 10 ml of growth media a day after starting the incubation.
   10. Monitor the gene expression.
      1. Monitor the gene expression without 4',6-diamidino-2-phenylindole (DAPI) staining. Using a fluorescent microscope, determine the percent of cells that are green. The percentage represents the transfection efficiency.
      2. Monitor the gene expression with DAPI staining.
         1. Wash the cells with phosphate buffered saline (PBS) three times.
         2. Fix the cells by adding 10 ml of 4% formaldehyde in PBS (10 min incubation at RT).
         3. Wash the cells with PBS three times.
         4. Incubate the cells in the dark for 15 min at RT with 8 ml of PBS containing 1:500 DAPI, 1% BSA, 0.01% digitonin.
         5. Wash the cells with PBS three times.
         6. Using a fluorescent microscope, determine the number of cells that are green/blue relative to those that are blue (**Figure 2** top panel). The calculated percentage represents the transfection efficiency.

2. Using the lentivirus overexpression system [10]
   1. Seed human embryonic kidney (HEK)293T cells in a 15 cm tissue culture dish (10% FBS in DMEM as their growth media).
      Note: When the cells are about 60-70% confluent, they are ready to be transfected.
   2. Add 162 µl of the transfection reagent to 1,133 µl of the reduced serum media in a microcentrifuge tube [11]. Avoid contact of the undiluted transfection reagent with the tube wall.
   3. Add 24 µg of pLL3.7 eGFP (or another construct), 15.6 µg of Rev response element (RRE), 6.0 µg of REV, and 8.4 µg of vesicular stomatitis virus glycoprotein (VSVG) into the transfection reagent/reduced serum media mixture.
   4. Incubate the mixture for 20 min at RT.
   5. Replace the growth media with 16 ml of 10% FBS in DMEM.
   6. Add the DNA/transfection reagent/reduced serum media mixture drop-wise to the dish.

7. Gently shake the dishes several times in a forward and backward direction followed by a leftward and rightward direction. It is normal to see some of the HEK293T cells detached at this point.
8. Place the dish in the incubator.
9. After 24 hr of incubation, replace the media in the dish with 25 ml of growth media.
10. On the following day, collect the growth media containing the lentivirus (first collection).
11. Repeat step 2.2.10 to collect more lentivirus (the second collection).
12. Pool the first and the second collection, and remove cell debris by centrifugation (2,500 x g for 5 min).
13. Filter the collection with a disposable bottle-top filter (0.45 µm pore), and concentrate the virus by centrifuging the collection at 31,400 x g for 2 hr at RT (JA-20 rotor). Mark the bottom of the centrifuge tube where the pellet is located. Decant the supernatant, and leave the tube inverted at RT for about 15 min.
14. Resuspend the virus-containing pellet with 100 µl of 1X PBS. Avoid bubbles.
15. Store the concentrated virus at -80 °C. Avoid freeze-thaw cycles.
16. Determine the optimal amount of virus needed to transduce the Caco-2 cells by titration. To save cost, use a 24-well plate (0.3 ml of growth media/well) instead of a 10 cm tissue culture dish for titration.
    1. Add increasing amounts of the concentrated virus (0, 1, 2, 5, 10, 25, and 50 µl/well) supplemented with polybrene (final concentration = 5 µg/ml) to the 40-70% confluent Caco-2 cells. Shake the 24-well plate gently as described in 1.1.2.
    2. Monitor their gene expression (Step 2.1.10.) (**Figure 2** bottom 4 panels).
17. Since the expression of transgene is generally sustained, maintain the transduced cells for future experiments and continuously monitor their gene expression (Step 2.1.10.).

3. Stimulating the Lipoprotein Secretion

1. Using the regular tissue culture dish
    1. Prepare a 100X lipid mixture by mixing 50 mg of oleic acid, 40 mg of lecithin, and 48 mg of sodium taurocholate. Bring the volume to 900 µl with PBS (enough for 8 dishes). Vortex the lipid mixture vigorously.
    2. Add 900 µl of the 100X lipid mixture into 89.1 ml of growth media. Mix, and filter the lipid-containing media. The final concentrations (1X) of oleic acid, lecithin, and sodium taurocholate are 2.0 mM, 1.36 mM, and 1.0 mM, respectively.
    3. Add 10 ml of the lipid-containing media to the cells.
    4. Incubate the cells with the lipid-containing media for 4 hr in a 37 °C incubator.
    5. Wash the cells with PBS three times.
    6. Add 10 ml of the growth media to the cells to collect the lipoprotein secretion.
    7. Incubate for 2 hr in a 37 °C incubator.
    8. Collect the lipoprotein-containing media.
2. Using the permeable membrane system
    1. Follow steps 3.1.1-3.1.2 to prepare the lipid mixture.
    2. Add 10 ml of the lipid-containing media to the apical chamber and 10 ml of the growth media to the basolateral chamber.
    3. Incubate for 4 hr in a 37 °C incubator. Collect the lipoprotein-containing media in the basolateral chamber.

4. Lipoprotein Isolation (Figure 3)

1. Remove the cell debris from the lipoprotein-containing media by centrifugation (2,000 x g for 5 min).
2. Decant the media into a 50 ml tube.
3. Add 5.95 g of sodium chloride to the media.
4. If the sample will be analyzed by the TEM, add 1 protease inhibitor cocktail tablet to maintain the integrity of the lipoproteins.
5. Bring the volume to 23 ml with water (1.2 g/ml NaCl density solution).
6. Dissolve the solutes completely.
7. Decant all of the solution into a polycarbonate ultracentrifuge tube.
8. Gently overlay the 1.2 g/ml density solution with 0.5 ml water (1.0 g/ml density).
9. Balance the tube by weight and not by volume.
10. Gently load the tubes in the T865 rotor.
11. Spin the samples in the ultracentrifuge at 429,460 x g for 24 hr at 4 °C.
12. Immediately isolate the top 0.5 ml solution by gentle pipetting. Keep the tube as still as possible.

5. TEM Analysis

1. Prepare 5 ml of 2% phosphotungstic acid (w/v) and adjust the pH to 6.0.
2. Filter the 2% phosphotungstic acid with a syringe filter (pore size: 0.2 µm).
3. Drop 20 µl of the lipoprotein sample on a sterile dish.
4. Drop 20 µl of the filtered 2% phosphotungstic acid next to the sample on the same dish.
5. Gently drop an EM grid with the dull side resting on the sample.
6. Incubate at RT for 1 min.
7. Gently tap the side of the EM grid on a filter paper to remove the sample from the grid.
8. Gently drop the EM grid with the dull side resting on the 2% phosphotungstic acid.
9. Incubate at RT for 1 min.

10. Gently tap the side of the EM grid on a filter paper to remove the phosphotungstic acid from the grid.
11. Using a TEM, capture the images of the lipoproteins (**Figure 4**).

Representative Results

Figure 1 displays normal 13-days post-confluent Caco-2 cells. The appearance of dome-shaped structures and intracellular lipid droplets are characteristic of differentiated Caco-2 cells. When the Caco-2 cells are not dispersed equally during seeding, they will clump and overgrow in certain areas of the dish; and there will be a few areas in the dish without any cells. Swirling and placing the dish on a slanted surface should be avoided. It is also important to note that post-confluent Caco-2 cells are more susceptible to detachment when new growth media is added to the cells too roughly. Therefore, the new media should be added gently to prevent cell detachment.

Based on these studies, the transfection efficiency of Caco-2 cells was between 30-60% (**Figure 2** top panels). In contrast, the transduction efficiency of Caco-2 using the lentivirus expression system was approximately 100% (**Figure 2** bottom panels). **Figure 2** also showed that the optimal amount of concentrated lentivirus was 10 µl. The transduced Caco-2 cells were maintained up to 12 passages. As shown, even after 12 passages the transduced cells still expressed eGFP. The transduction efficiency clearly depends on the lentivirus concentration. The confirmation of the transfection/transduction efficiency is critical, and should be performed as a routine preliminary analysis prior to the actual experiments. Although Western blot analysis can be used to estimate the percent increase of the gene expression, it should not be the primary method to determine the transfection/transduction efficiency.

Using the NaCl density gradient ultracentrifugation method (**Figure 3**), the lipoproteins secreted by the Caco-2 cells were isolated and analyzed on a TEM. Some of the chylomicrons, lipoproteins larger than 80 nm in diameter, were depicted in **Figure 4**. The smaller lipoproteins, VLDLs, were also present. It is essential to confirm the successful isolation of both chylomicrons and VLDLs on a TEM. As previously discussed [8], biochemical analysis should not be the primary method of confirmation. The absence of lipoproteins, specifically chylomicrons, indicates that the lipid transport by the Caco-2 cells is not efficient. Consequently, they will not serve as a good model to study lipid transport. The number of chylomicron particles relative to the total number of lipoprotein particles can be counted [8]. A high percentage indicates efficient lipid transport.

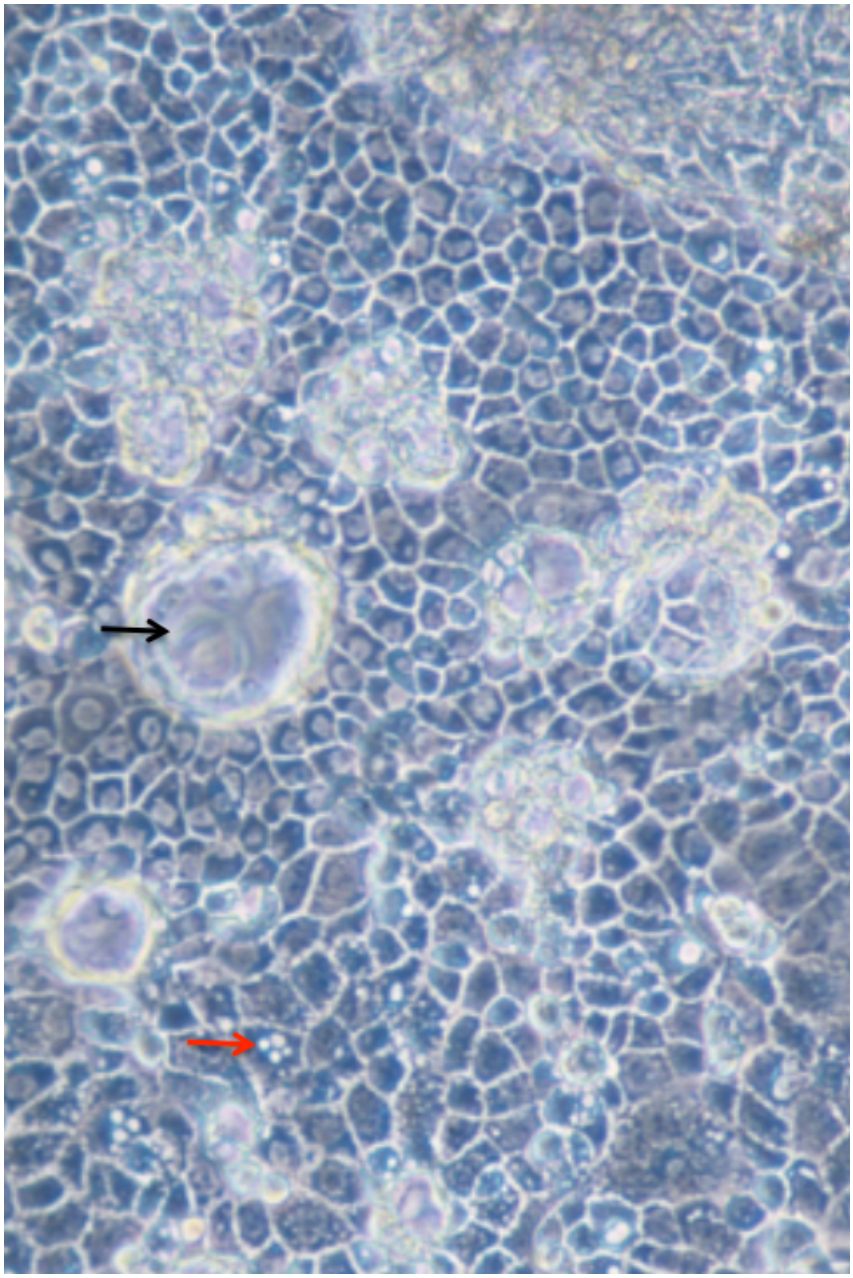

Figure 1. Representative micrograph of 13-day post-confluent Caco-2 cells. Intracellular lipid droplets are visible in some cells (red arrow). The unique dome-shaped structures (black arrow) formed by some Caco-2 cells are generally present only after the cells have reached confluence. Magnification = 100X. Please click here to view a larger version of this figure.

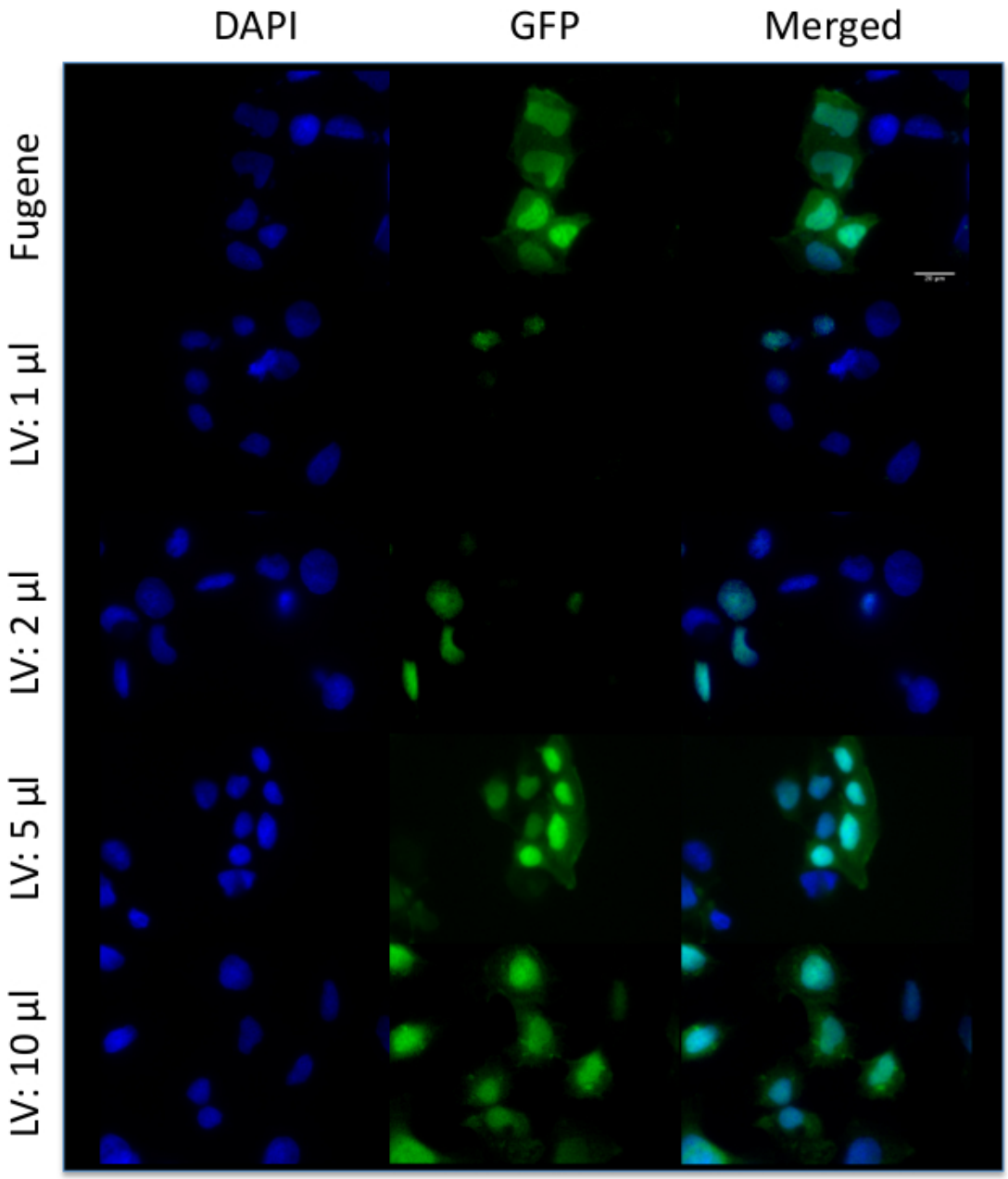

Figure 2. Comparison of the effectiveness of the lipid-based transfection and the lentivirus expression system. Top panel: Caco-2 cells were transfected with pLL3.7 eGFP using the non-liposomal transfection reagent (Scale bar = 20 µm). Bottom 4 panels: Caco-2 cells were transduced with pLL3.7 eGFP using the lentivirus expression system with varying amounts (1, 2, 5, or 10 µl) of the concentrated lentivirus (LV). The displayed cells were from the 12th passage of the original transduced cells. The left panels show the DAPI staining, the middle panels show the GFP fluorescence, and the right panels show the merged images. The lentivirus expression system was evidently more effective than the lipid-based transfection. Please click here to view a larger version of this figure.

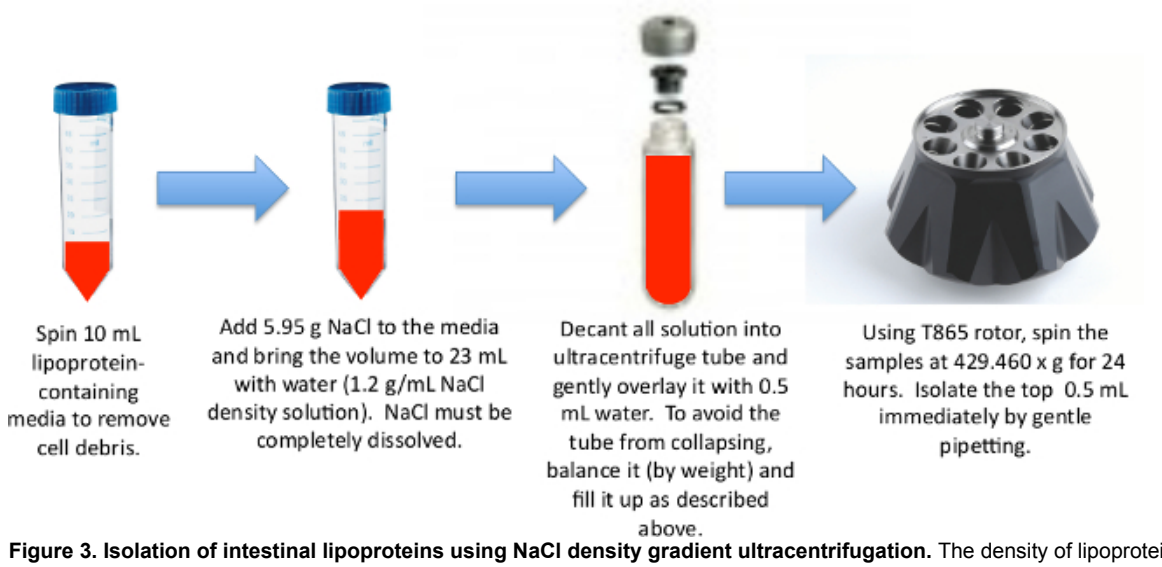

Figure 3. Isolation of intestinal lipoproteins using NaCl density gradient ultracentrifugation. The density of lipoprotein-containing media is adjusted to 1.2 g/ml by adding the appropriate amount of NaCl. The volume of the sample also needs to be adjusted so that it will fill the entire ultracentrifuge tube to prevent collapse. To achieve a density gradient, 0.5 ml of water is overlaid gently on the 1.2 g/ml density solution. The sample is then spun at 429,460 x g for 24 hr using a T865 rotor (equivalent to 2.15 Svedberg units). The intestinal lipoproteins should be immediately recovered by gentle pipetting. Please click here to view a larger version of this figure.

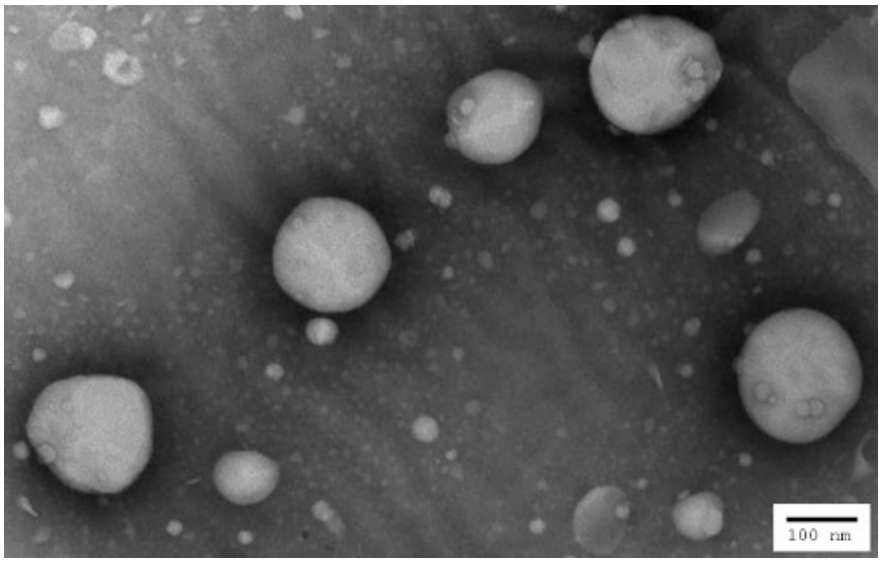

Figure 4. Representative electron micrograph of the lipoproteins produced by the Caco-2 cells. The lipoproteins isolated by NaCl density gradient ultracentrifugation were negatively stained with 2% phosphotungstic acid (pH 6.0). Chylomicrons, lipid particles larger than 80 nm in diameter, and VLDLs, those smaller than 80 nm, are both present. Scale bar = 100 nm. Please click here to view a larger version of this figure.

Discussion

In this paper, the two systems that can be used to maintain Caco-2 cells are described, namely, the regular tissue culture dish and the permeable membrane. The benefits of using the permeable membrane system include the separation of the apical and the basolateral compartments, and the ability to incubate the lipid mixture and collect the lipoprotein secretion simultaneously. However, the permeable membrane inserts are expensive, and their polycarbonate membrane does not allow for good cell visibility. One of the advantages of this *in vitro* model is that genetic manipulation studies will be more economical and less time-consuming. For better effectiveness, the lentivirus expression system should be used. The transduced Caco-2 cells generally maintain the expression of their transgene.

The ability of Caco-2 cells to produce chylomicrons is of paramount importance. Without this ability, Caco-2 cells would not be able to efficiently transport lipophilic materials, including but not limited to liphophilic drugs, vitamin A, D, E, and K, and any lipid-soluble nutrients. The proper methods to challenge Caco-2 cells to produce both VLDL particles and chylomicrons are described. The successful isolation of these lipoprotein particles should be confirmed on a TEM. Based on the current literature, this Caco-2 model offers the most efficient lipid transport among other Caco-2 models [12–14]. However, the *in vivo* lymph cannulation model still transports lipids more efficiently than any *in vitro* model. The underlying reasons have been recently discussed [8], namely because Caco-2 cells produce 2 different isoforms of apolipoprotein B, Caco-2 cells can't synthesize triglycerides from monoglycerides, and the serum component critical for chylomicron biogenesis may be lower in the growth media. It

is also important to realize the limitation of this *in vitro* model; this *in vitro* model excludes some potential important factors, such as gut motility, anatomy of the gut, and the interaction with other organ systems.

The main factors that allow Caco-2 cells to produce chylomicrons efficiently are the type/amount of lipids used and cellular differentiation [8]. Without the proper combination of these factors, Caco-2 cells will not produce a significant number of chylomicrons [8]. Of note, NaCl density gradient ultracentrifugation should be performed properly. The successful isolation of lipoproteins depends on timing (immediate without significant delay), good sample handling (sturdy without much agitation), and careful pipetting (getting only the top layer). Proper technique can be practiced by using pre-stained lipids to help visualize the lipoprotein layer [8]. Besides TEM, biochemical analyses, *i.e.*, apolipoprotein B and triglyceride analyses, can also be used to confirm the successful isolation of lipoproteins. These biochemical analyses, which we have previously reported [8], can also serve as methods in quantifying absorption. However, TEM should still be performed due to the tendency of the lipoproteins to aggregate[2], causing a potential overestimation of chylomicron production.

This *in vitro* model is particularly useful for studying dietary fat absorption and intestinal absorption of lipophilic drugs, vitamins, and other lipid-soluble nutrients. It can also serve as a model to improve poor bioavailability of oral lipophilic drugs. Since lipid-soluble materials are packaged into chylomicrons by enterocytes for transport to the circulation, chylomicron-producing Caco-2 cells will be more efficient in absorbing lipophilic drugs. In addition, this model allows investigators to determine the role of a specific gene in drug absorption by the gut (pharmacogenetics). It also allows investigators to compare the effect of various dietary fats on oral lipophilic drug bioavailability. All of these applications have been discussed previously [6].

Disclosures

The author has nothing to disclose.

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References

1. Drover, V. A., *et al.* CD36 deficiency impairs intestinal lipid secretion and clearance of chylomicrons from the blood. *J Clin Invest.* **115**, (5), 1290-1297 (2005).
2. Nauli, A. M., *et al.* CD36 is important for chylomicron formation and secretion and may mediate cholesterol uptake in the proximal intestine. *Gastroenterology.* **131**, (4), 1197-1207 (2006).
3. Nauli, A. M., Zheng, S., Yang, Q., Li, R., Jandacek, R., Tso, P. Intestinal alkaline phosphatase release is not associated with chylomicron formation. *Am J Physiol Gastrointest Liver Physiol.* **284**, (4), G583-G587 (2003).
4. Lo, C. -M., *et al.* Why does the gut choose apolipoprotein B48 but not B100 for chylomicron formation. *Am J Physiol Gastrointest Liver Physiol.* **294**, (1), G344-G352 (2008).
5. Jandacek, R. J., Heubi, J. E., Tso, P. A novel, noninvasive method for the measurement of intestinal fat absorption. *Gastroenterology.* **127**, (1), 139-144 (2004).
6. Nauli, A. M., Nauli, S. M. Intestinal transport as a potential determinant of drug bioavailability. *Curr Clin Pharmacol.* **8**, (3), 247-255 (2013).
7. Tso, P., Nauli, A., Lo, C. M. Enterocyte fatty acid uptake and intestinal fatty acid-binding protein. *Biochem Soc Trans.* **32**, (Pt 1), 75-78 (2004).
8. Nauli, A. M., Sun, Y., Whittimore, J. D., Atyia, S., Krishnaswamy, G., Nauli, S. M. Chylomicrons produced by Caco-2 cells contained ApoB-48 with diameter of 80-200 nm. *Physiol Rep.* **2**, (6), (2014).
9. Rubinson, D. A., *et al.* A lentivirus-based system to functionally silence genes in primary mammalian cells, stem cells and transgenic mice by RNA interference. *Nat Genet.* **33**, (3), 401-406 (2003).
10. Li, M., Husic, N., Lin, Y., Snider, B. J. Production of lentiviral vectors for transducing cells from the central nervous system. *J Vis Exp.* (63), e4031 (2012).
11. Pottekat, A., *et al.* Insulin biosynthetic interaction network component, TMEM24, facilitates insulin reserve pool release. *Cell Rep.* **4**, (5), 921-930 (2013).
12. Van Greevenbroek, M. M., van Meer, G., Erkelens, D. W. Effects of saturated, mono-, and polyunsaturated fatty acids on the secretion of apo B containing lipoproteins by Caco-2 cells. *Atherosclerosis.* **21**, (1), 139-150 (1996).
13. Levy, E., Yotov, W., Seidman, E. G., Garofalo, C., Delvin, E., Ménard, D. Caco-2 cells and human fetal colon: a comparative analysis of their lipid transport. *Biochim Biophys Acta.* **1439**, (3), 353-362 (1999).
14. Luchoomun, J., Hussain, M. M. Assembly and secretion of chylomicrons by differentiated Caco-2 cells. Nascent triglycerides and preformed phospholipids are preferentially used for lipoprotein assembly. *J Biol Chem.* **274**, (28), 19565-19572 (1999).

