**A Case of Severe Insulin Resistance**

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**Preparation:** “Megan, Jade, and Joanna”

As homework and prior to the case discussion in class, get acquainted with the case.

* Read the following story as an introduction to the context and to get started on this case.

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Jade and Megan have been best friends since second grade. While in school they spent a lot of time in each other’s homes. Jade’s older sister, Joanna or Jo, was their favorite go-to person – for help with school projects, personal advice, teenage troubles, and so much more. A few years ago, Jo got married and now lives with her husband and little baby girl in Texas. Currently the three of them live in different cities – Megan is in Massachusetts, studying in Boston College, majoring in Biochemistry; Jade is in California studying in Los Angeles College of Music to become a pianist; and Jo is a nurse practitioner in Austin. Even though they live over 2600 miles away from each other Megan and Jade still keep in touch.

Last month, Jade called Megan on a Sunday afternoon and anxiously said – “Do you know Jo told me that she was recently diagnosed with Diabetes, something about insulin resistance or something?” “She is just 32, not obese, you know, and is very particular about what she eats and stuff”. Megan sensed that Jade was worried. She knew Jade’s mom and maternal grandma had been diagnosed with diabetes in their thirties too, so she wondered if Jade was worrying about developing diabetes herself. A little later Jade mentioned ““Jo even said that she got tested and confirmed that it is not a MODY, do you know what that is?” Megan didn’t know but said she would find out. That afternoon they talked on the phone for an hour about family history, food, obesity, and diabetes. By the time Jade hung up, Megan was seriously thinking about Jade’s chances of getting diabetes, and for that matter, Joanna’s baby girl too.

The next morning Megan decided she wanted to learn more about diabetes and MODY. During her “Intro to Research” course Megan had learned about PubMed, a free online search engine for scientific literature on biological and biomedical topics with links to access their abstracts and full articles. She started searching online to see if I could find anything that could help her understand if and how diabetes could indeed be inherited. Megan found out that Maturity Onset Diabetes of the Young (MODY) was caused by mutations in specific genes that can lead to diabetes. Then she remembered that Jo’s test results for MODYs was negative. Megan wanted to learn more about insulin resistance. One particular paper that really caught her attention was titled “A Family with Severe Insulin Resistance and Diabetes Due to a Mutation in AKT2”. The family tree shown in the paper seemed very much like Jade’s family, so she became curious and opened the paper to read it in detail.

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*The Familial Connection*

Q1. Draw a pedigree tree for Jade and Joanna’s family with currently known information about diabetes in the family.

* Read the abstract of the paper ([https://*doi*.org/*10.1126*/*science*.*1096706*](https://doi.org/10.1126/science.1096706)) that Megan found and let us join her in understanding what the paper described.

The paper describes the case of a nonobese 34-year-old female who developed diabetes at 30 years of age. The proband, her nonobese mother, her maternal grandmother, and a maternal uncle were all affected. The pedigree tree included in the paper shows the inheritance patterns of hyperinsulinemia and diabetes in the proband’s family. Here Proband is the individual/subject who brings a case to attention – e.g., the patient, or person who is being studied. Examine the figure 1D in the George et al., 2004 paper (also shown below for your convenience) and answer the following questions.

A map with text

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Figure 1D from George et al., 2004.

Q2. What is the relationship between hyperinsulinemia and diabetes mellitus in the three numbered generations [(i), (ii), (iii)] in the family tree shown above?

Q3. DNA sequencing of the proband’s genome and selected family members revealed a G-to-A mutation in the AKT2 gene, changing the codon for amino acid 274 from CGC to CAC. Consult the genetic code (<https://www.genome.gov/genetics-glossary/Genetic-Code>) and list what mutation was seen in the proband.

Q4. Is the mutated residue side chain similar to or different from that found in the native protein? Draw the chemical structure of the side chains of these amino acids and explain in terms of the size and physicochemical properties.

**Part 1: Understanding Insulin Resistance**

The supplementary sections of the paper provide details on how members of the proband’s family with the AKT2 mutation had hyperinsulinemia – i.e., even when no or very little glucose was consumed these individuals produced higher amounts of insulin compared to control subjects from the population. Yet, many of these individuals developed diabetes.

*Box 1: Concept*

**Insulin** binding to **Insulin receptors** on the cell surface of a muscle cell initiates a series of signaling steps involving various players that eventually signal vesicles containing the Glucose transporter (GLUT4) to move to the cell membrane where they open to let in glucose from the blood into the cells.

If any of the signaling steps are missing or not functioning properly the signal to move GLUT4 transporters to the cell membrane can be disrupted as seen in insulin resistance.

To better understand Insulin resistance let us learn a little more about insulin signaling and the role of AKT2 using a resource called KEGG.

*Box 2: Resource*

Kyoto Encyclopedia of Genes and Genomes (**KEGG**, <https://www.genome.jp/kegg/>) has aggregated information about various types of biological interactions at the molecular, cellular, organismal, and ecosystem levels.

**KEGG Pathway** (<https://www.genome.jp/kegg/pathway.html>) is a collection of metabolic and signaling pathways in health and disease. This can be consulted to explore the names and interactions of key players in these pathways.

Go to the KEGG Pathway website and search for insulin resistance (either by typing it in the top search box or by looking through the Human Disease pathways). Save an image below.

Follow the pathway(s) from Insulin (INS) binding to Insulin Receptor (INSR) on the left of the page to GLUT4 vesicles being moved to the membrane for glucose uptake.

Q1. Identify all the key players in the shortest path that connects Insulin to GLUT4 and list them in sequential order. Does this involve Akt2?

The George et al., 2004 paper that Megan was reading showed that the mutant AKT2 enzyme’s activity is altered. The AKT2 gene with and without the mutation was introduced into a mammalian cell line and the protein was expressed. Results of a kinase assay (Figure 2B) shows enzyme activity for both the wild type and mutant proteins, with (Ins) and without adding Insulin (Bas). Examine the figure (also shown below for your convenience) and answer the following questions.

A screenshot of a cell phone

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Figure 2B from George et al., 2004.

Q2. In the kinase assay results, the activity of the wild type protein changes significantly in the presence of insulin. Describe the change and explain why this change is observed in the presence of insulin? (Hint: examine the KEGG pathway and consider the insulin signaling steps in writing this answer).

Q3. What does the kinase assay results tell you about the activity of the H274 mutant in comparison with the wild type AKT2 enzyme?

Q4. Examine the KEGG pathway and explain the impact of inactivating the AKT2 enzyme. Why and how does this lead to insulin resistance?

**Part 2: Insulin Resistance in Molecular Detail**

Megan wanted to “see” how a single mutation in AKT2 can impact insulin-signaling in such a big way. She also wanted to understand why changing the Arg at position 274 to His would have such a big effect on the activity of the enzyme. She decided to look at the structure of the protein in atomic detail, so went to the Protein Data Bank.

*Box 3: Resource*

RCSB Protein Data Bank (**RCSB PDB**, [www.rcsb.org](http://www.rcsb.org)) provides access to 3D structural data of biological macromolecules (proteins, nucleic acids, carbohydrates and their various complexes). In addition, it provides information about the experiment used to derive the data, details about the molecules included in the experiment, and links to various bioinformatics resources that can provide additional information about the protein/molecule of interest. Each structure in the PDB is identified by a unique identifier (called PDB ID). Atomic coordinates form the PDB can be visualized and analyzed using various visualization software (some available from RCSB PDB).

Search for AKT2 protein structures in the PDB ([www.rcsb.org](http://www.rcsb.org)) to see what structure(s) is/are available. Type in the protein name AKT2 in the top search box and click on the Protein Kinase AKT2 under UniProt molecular name (in the suggestions box that opens up). Examine the list of PDB structures that match this query and answer the following:

Q1. List the PDB identifiers and titles for the 2 structures that contain AKT2 protein – (one in its inactive form and one where it is activated).

Ans:

|  |  |
| --- | --- |
| PDB ID | Title |
|  |  |
|  |  |

When identifying the relevant PDB structures keep the following ideas in mind:

* Structures of **inactive enzymes** are often apoenzymes – i.e. without any substrate, cofactor etc. bound to it. In some instances, mutations in the active site residues will result in inactive enzyme – which does not function, even in the presence of relevant substrate(s) and cofactor(s).
* Structures of **active enzymes** are seen either as structures trapped in a transition state complex, with a substrate/ cofactor analog and or inhibitor bound. Some active enzyme structures may also be product complexes.

Q2. Can you tell from the structure title what the active and inactive AKT2 structures contain?

Open the structure summary pages to learn more about these two structures.

*Box 4: Resource*

***What can you find on the structure summary page?***

1. **Title** - that tells you what the structure is about

2. **Snapshot** - of what the structure of the molecule/complex looks like. *Note you can look at the deposited coordinates (called asymmetric unit) and one or more biological assemblies by clicking on the arrows above the image box*

3. **Authors** – who solved the structure

4. **Literature** – for access the article that describes the structure. *This section also includes links to PubMed page and the article’s abstract, when available.*

5. **Macromolecules** – All proteins and nucleic acids present in the structure are listed here. Each unique type of macromolecule or molecular chains is listed as a separate entity. There may be multiple copies of a molecule in the structure.

*Note their name, source, chain identifiers (IDs) and links to the protein sequence database (UniProt). Large proteins with multiple domains may be cut into smaller pieces – a short peptide or a single domain and included in the experiment.*

6. **Small molecules** – All ligands, ions, cofactors, inhibitors that are present in the structure are listed here.

*You can find links here to explore the interaction of this ligand with the target protein.*

7. **Experimental details** – describe details about the structure determination

8. **Structure quality** – shows a slider that provides insights about the quality of the structure and its agreement with the experimental data and geometric standards.

See <http://pdb101.rcsb.org/learn/guide-to-understanding-pdb-data/introduction> for details

Q3. Explore the structure summary pages for both entries to complete the table below.

Ans:

|  |  |  |
| --- | --- | --- |
| Inactive AKT2 PDB ID: | Authors of entry |  |
| Macromolecules |  |
| Small molecules |  |
| Activated AKT2 PDB ID: | Authors of entry |  |
| Macromolecules |  |
| Small molecules |  |

Q4. Click on the 3D View tab on the Structure summary page of the inactive AKT2 structure and view it. What is the overall shape of the protein? Where are the different secondary structural elements (alpha helices and beta sheets) located in this structure? Take a screen shot of the structure and include it here.

In order to visualize and analyze the AKT2 structures in greater detail we will use an online molecular structure visualization tool, called iCn3D.

*Box 5: Resource*

**iCn3D** is a web-based visualization tool that allows users to directly open any structure from the Protein Data Bank (PDB) and visualize the structure. Users can interactively rotate the molecule/complex, select specific regions and represent them in different ways, compare structures, analyze interactions and make simple distance measurements.

* Go to iCn3D (<https://www.ncbi.nlm.nih.gov/Structure/icn3d/full.html>)
* Click on the button called File >> Retrieve by ID >> PDB ID so that a new window opens. Input the PDB ID of the structure you wish to visualize (e.g., 1o6k) and click on Load.
* Spend a few minutes playing around with the different pull-down menus to see some of the different ways this protein view can be adjusted.
* Orient the molecule so that you can clearly see all components present in the structure. Save an image by clicking on File >> Save files >> iCn3D PNG image.

Q5. Where are the substrate and cofactor molecules in this structure? Import the image saved above to power point or any other graphics software and label in the image appropriately.

*Box 6: A Mini Lesson on AKT2*

**AKT2** is a Serine/Threonine protein kinase that is itself activated by phosphorylation at Thr309 and Ser474. During the activation of this enzyme, the enzyme PI3K phosphorylates Thr309, while Ser474 is phosphorylated by mTORC2. Thus, AKT2 aggregates signals from multiple proteins and functions as a signaling node.

To study the activated form of AKT2, Thr309 and Ser474 may be phosphorylated or mutated (to Glu and Asp, respectively) to mimic the phosphorylated amino acids charge and interaction.

To learn more read the review article Cell. 2007 Jun 29; 129(7): 1261–1274. doi: 10.1016/j.cell.2007.06.009

A linear schematic of the AKT2 protein showing the domains, specific amino acid residues that are phosphorylated, and the one that was mutated in the proband is shown in Figure 1B (shown below for convenience).

A close up of text on a white background

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Figure 1B from George et al., 2004.

Let us now locate this specific residue that was mutated in the proband (R274) in the 3D structure.

* Click on the button called Windows >> View Sequences & Annotations.
* Click on the Details button to see the one letter code sequence of all the protein chains in the structure.
  + Locate the R274 in the sequence, click and drag on the residues in the sequence and annotation window. The residues will be highlighted in yellow, both in the sequence and graphics windows.
  + Click on Style >> Side chain >> Stick. Now color this amino acid by clicking on Color >> Unicolor >> Cyan.

Q6. Where is this amino acid located in relation to the active site, substrate, and cofactors?

Explore the neighborhood of this residue to find out why changing it to His has a big impact on the enzyme activity.

* While the R274 is selected (highlighted in yellow), click on Select >> by distance >> a new window opens. Click on Display.
  + Now show the sidechains of the selected amino acids by clicking on Style >> Side chain >> Stick and color these amino acids by clicking on Color >> Atom.
* To show the hydrogen bonds and other interactions between the highlighted amino acids click on View >> H-bonds & interactions. In the new window that opens select the types of interactions to view, (H-bonds, salt bridges, etc. except contacts/interactions), keep the default options and click on Display. The interactions should be shown in dashed lines.
* Zoom in on the selected residues by clicking on View >> Zoom in selection.

*Box 7: Concept*

Biomolecular structural stability, interactions and functions are dependent on various non-covalent interactions. Some key interactions in molecular structures are

**Hydrogen bonds** - formed between two partially negatively charged atoms with a hydrogen atom between and covalently linked to one of them. e.g. in structures look for examples of O/N … H\_\_O/N, where … denotes hydrogen bond and \_\_ denotes a covalent bond

**Salt bridges** or **ionic interactions** - formed between oppositely charged amino acid side chains and/or charged ligands/ions. e.g. in structures look for interactions between Lys/Arg/His and Glu/Asp. These interactions may also involve phosphate groups and ions such as K+, Na+, Cl- etc.

**Hydrophobic interactions** - formed between hydrophobic amino acid side chains positioned away from the aqueous environment. e.g. look for regions with large numbers of carbon and hydrogen atoms in close proximity. Aliphatic amino acids such as Ala, Leu, Val, Ile participate in hydrophobic interactions.

**Pi stacking** - seen between amino acids with aromatic side chains. Pi clouds of aromatic rings interact with each other in staggered stacks, face to edge interactions, or interactions with positively charged amino acid side chains (pi-action interaction).

Learn more at <https://earth.callutheran.edu/Academic_Programs/Departments/BioDev/omm/jsmolnew/bonding/chymo.html#Topic2>

Q7. What does the R274 side chain interact with? What do you think is important about this interaction? (Examine the neighboring region to answer this question and support your answer with a suitable molecular illustration).

Figure 2B in the George et al., 2004 paper shows the relative orientation of R274 and the phosphothreonine at 309 (see below).

A picture containing text, map

Description automatically generated

Redraw the above figure using the iCn3D tool and show the sidechains of R274, pT309, D275, H196, and S9 (in the GSK3 peptide). Once you have oriented the structure in the above view, you can measure distances between atoms as follows:

* Click on View >> Distance >> Measure – a new window opens with entitled “Measure the distance of …”
* Identify the atoms between which you would like to measure the distance. Click on them while holding the Alt key to select them both. (If you are unable to select both atoms click on one atom with the Alt key pressed and then click on shift + Alt + the second atom. Now click on Display in the “Measure the distance of …” box.
* Note down the distance displayed in the graphics screen.

Q8. Which atoms in R274 and pT309 are closest to each other? What the distance of closest approximation between R274 and pT309? What interactions exist between these atoms? Illustrate your answer with a screenshot of this measurement.

In the proband, the R274 is mutated to His. Examine the side chains of Arg and His and measure distances as described above.

Q9. What is the closest distance of approximation between His and pT309? (Hint: use an equivalent atom in Arg to represent the His atom that would be present in the mutant.). How would the interactions between amino acid 274 and 309 change in the mutant? Include suitable molecular images to support your answer.

Back to the Megan, Jade, and Joanna story …

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When Megan had read through the paper, she was excited that she understood how the single mutation in AKT2 could result in insulin resistance and diabetes. However, she was also concerned – if the R274H mutation reduced the kinase activity, all signaling molecules downstream of AKT2 would not be able to pass on the signal to facilitate glucose uptake by cells. In fact, if any of the signaling molecules in the complex insulin signaling pathway was missing or non-functional it could lead to insulin resistance and diabetes. Megan also realized that many of the current diabetes treatment approaches either promote insulin secretion or inject more insulin into the system. Ironically, in the case of insulin resistance, all these approaches would probably not be helpful. For the past few weeks Megan has been wondering – how did they treat the proband and other individuals in their family?

**Part 3: Bypassing the Roadblock**

Two weeks ago, when Megan was walking by the departmental notice board, she stopped as she read the title – “Insulin Resistance and Improvements in Signal Transduction”. Wow! She thought this is exactly what she had been wondering about since she had read the George et al., 2004 paper. She decided to attend that seminar. The speaker, Dr. Laurie Goodyear, was a researcher at Joslin Diabetes Center, Boston, and spoke about the role of physical exercise in reducing blood glucose levels in type 2 diabetes. In this lecture Megan learned about insulin-independent glucose uptake!

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Examine the following simple figure from Dr. Goodyear’s seminar and notice the crosstalk between insulin dependent and insulin independent glucose uptake in skeletal muscle cells.

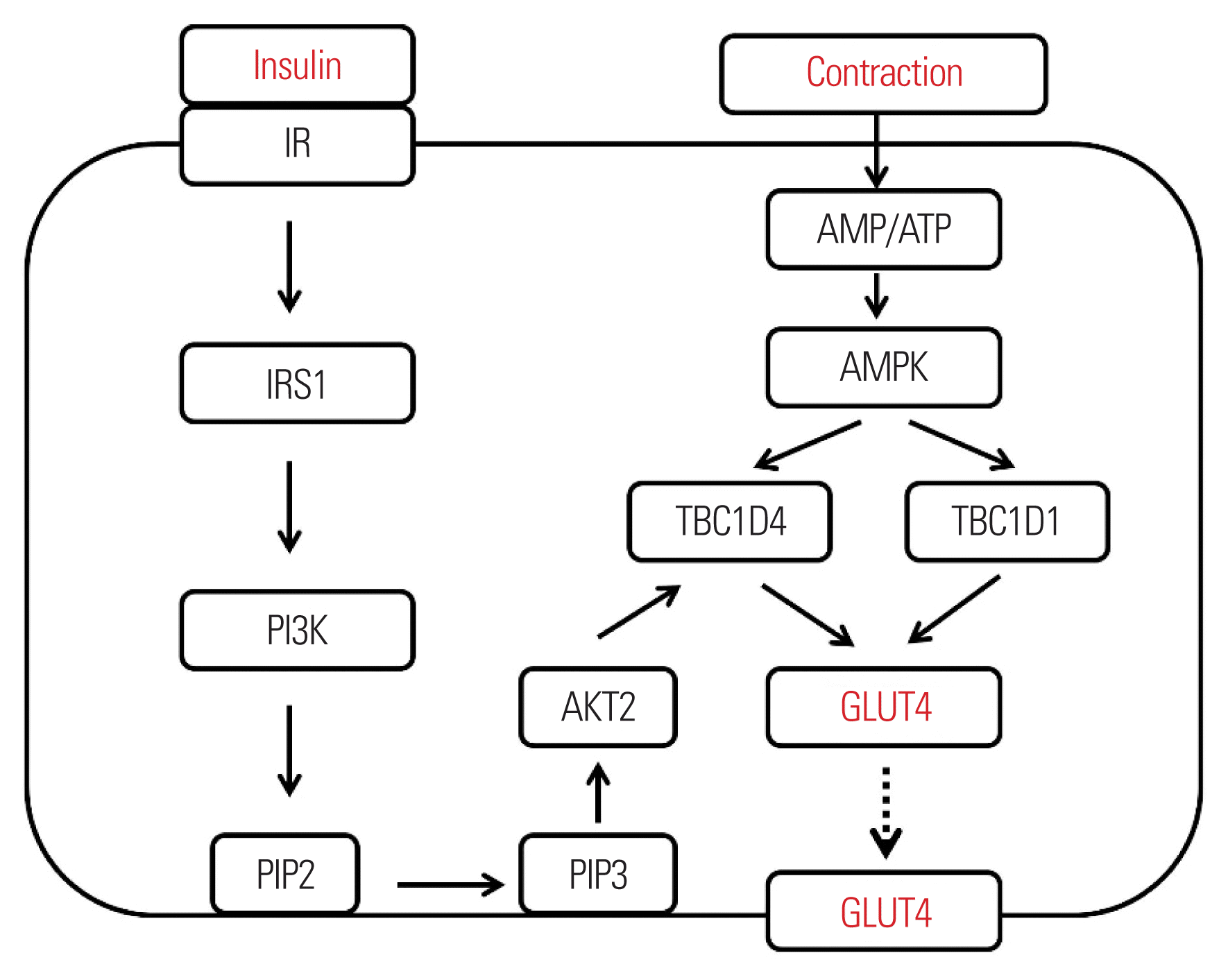


Figure 1. Journal of Obesity & Metabolic Syndrome 2018; 27(3): 150-157. doi: 10.7570/jomes.2018.27.3.150.

In the above figure do you notice that exercise uses up cellular ATP, activates AMP kinase, which in turn acts on TBC1D1 and TBC1D4 to facilitate the transport of GLUT4 receptors to the cell membrane for glucose uptake? So now even when the insulin signaling fails this pathway can be activated!

Megan was really excited and wants to write an email to Jade to explain all the things that she has found out about insulin resistance, its cause, and treatment approaches.

Q1. Help Megan write 1-2 paragraphs (5-10 sentences) to explain insulin resistance and possible ways to manage it. Feel free to add an image to help explain your point(s).