

Physiopathology of oxygen transport: the “Apple Ropeway” metaphor

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ABSTRACT

Oxygen balance is fundamental to human life, requiring a delicate equilibrium between oxygen delivery (DO_2) and consumption (VO_2). While these physiological principles are critical for bedside clinicians, they are often perceived as complex. This article introduces a novel educational metaphor, the “Apple Ropeway”, inspired by a real-world system in Trentino, Italy, to describe oxygen transport and extraction in lay terms.

In this model, the circulation acts as a ropeway, the heart serves as the engine, hemoglobin molecules are the cabins, and oxygen molecules are the apples being transported from the loading station (lungs) to the market (tissues). The system illustrates how DO_2 depends on cardiac output, hemoglobin concentration, and arterial saturation. The metaphor effectively reflects human physiology under various conditions, including physical exercise, chronic hypoxemia, anemia, and shock. Furthermore, it clarifies complex scenarios like carbon monoxide poisoning and metformin intoxication, where oxygen binding or tissue consumption is impaired. Despite necessary simplifications (e.g., local heterogeneity is not taken into account), the apple ropeway metaphor provides an intuitive framework. By translating clinical variables into mechanical counterparts, this approach aims to help younger clinicians understand the crucial principles of oxygen transportation monitoring.

Keywords: Oxygen delivery, Oxygen consumption, Hemoglobin, Shock, Medical education

Oxygen is a crucial molecule in human life, since it allows the production of energy in the cells by aerobic reactions. Oxygen is transferred from the atmosphere to the blood in the lungs and then delivered by circulating blood to the tissues (Oxygen Delivery: DO_2), which consume a given amount of oxygen (VO_2). Balance between DO_2 and VO_2 is a crucial element of homeostasis, and it is reflected by the fraction of delivered oxygen that the tissues consume ($ERO_2 = VO_2/DO_2$) (1). In physiological conditions, several mechanisms are in place so that any change in VO_2 (e.g., increase during physical exercise) is reflected by simultaneous changes in DO_2 . Several pathological conditions, primarily affecting the respiratory and cardiovascular system, may lead to a reduction of DO_2 , so that ERO_2 increases. DO_2 depends on a limited number of variables, and ERO_2 can be easily inferred by measuring the central venous saturation of oxygen; their proper understanding may be greatly informative for bedside clinicians (2,3).

Albeit sometimes considered a complex topic, the physiology behind it is quite straightforward. Several metaphors (e.g., trains, bank accounts) have been used to describe the system principles and interpretations of the different variables collected.

Recently, I was inspired by the inauguration of the “Apple Ropeway” in Trentino (4), and I found this to be a great model to describe, in lay terms, the normal functioning of the DO_2/VO_2 system and its modifications under several physiological and pathological conditions. The translation of the DO_2/VO_2 model to the apple ropeway metaphor implies some simplifications, mainly that the model considers only one global DO_2 and VO_2 without taking into account local heterogeneity, which may be extremely relevant, especially in maldistributive shock (5). The shape of hemoglobin dissociation curve and dissolved oxygen are neglected. Finally, oxygen in itself is not a source of energy (as opposed to apples).

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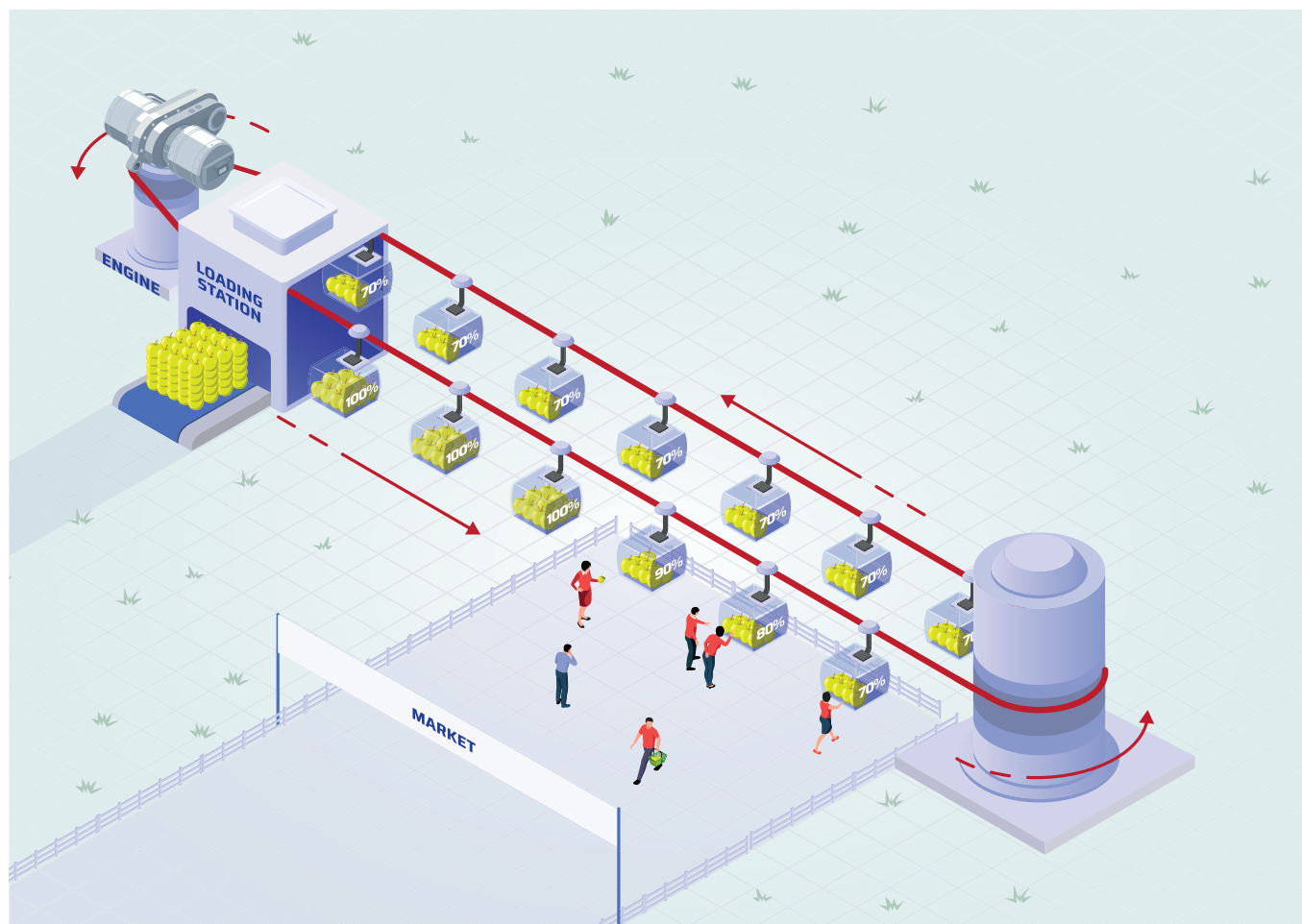


FIGURE 1 - System description.

| Actual human physiology | Apple ropeway metaphor |
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| <p>System description (Fig. 1)</p> | <p>Apples (oxygen) are delivered from the loading station (lungs) to the market (tissues) by a ropeway (circulation): a rope (blood), circulates between the two extremes, is pulled by an engine (heart). Apples are carried on the ropeway in cabins (hemoglobin), which have a given distance on the rope, and each cabin can carry a given amount of apples. Hence, the total amount of apples that may be delivered from loading to the market (DO_2) depends on three factors: the frequency of the cabins of the rope (hemoglobin concentration), the loading of apples in each cabin (hemoglobin saturation) and the speed of the rope (cardiac output). In the actual ropeway, a fully loaded cabin carries about 300 kg of apples, and cabins travel at a speed of 5 m/s for a total traveling capacity of 150 tons/hr.</p> |
| <p>The blood is propelled from the heart towards peripheral tissues (where hemoglobin releases oxygen) by arterial vessels and returns to the heart by the venous vessels.</p> | <p>The rope is pulled from an engine (heart) close to the loading station. The rope has an outbound branch (arterial vessels), reaches the unloading station (peripheral tissues) and an inbound direction (venous vessels)</p> |
| <p>Lungs are very efficient in oxygenating the blood and the hemoglobin gets almost fully saturated with oxygen (Sat_{art} 97-98%). The main determinant of hemoglobin saturation is alveolar (and capillary) oxygen partial pressure.</p> | <p>In the loading station the system is very efficient, so that each cabin passes through the station, has enough time to become -almost- fully loaded 97-98 % of loading capacity (Arterial saturation) and leaves. To load each cabin, piles are put in stacks, whose height (partial pressure of oxygen) determines the relative filling of each cabin.</p> |

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In normal conditions tissues uptake about 30% of the oxygen which is delivered by circulation in order to fulfill the demands of cellular metabolism.

Unlike what happens in the real “apple ropeway,” let us imagine that, in the unloading station, there are some customers who consume a given amount of apples (VO_2) picking them up from the cabins and eating them. Normally, they eat about 30% of the apples that arrive at the station.

Hence, the hemoglobin returning from tissues to the right heart is about 70 % saturated (mixed central venous saturation, $ScvO_2$). This value is of paramount importance in understanding the tissue ERO_2 . A $ScvO_2$ of 70% indicates that, on average, the DO_2 is adequate to oxygen consumption (VO_2). If the $ScvO_2$ drops, this indicates that either the DO_2 has decreased or the VO_2 has increased, or both.

Hence, the cabins return to the loading station with a 70% filling (mixed venous hemoglobin saturation, $ScVO_2$). As the company wants to make sure that there are always enough apples for the customers, the amount of apples returned to the loading station is a parameter of paramount importance. A cabin returning with a 70% load indicates that the apples delivered were more than enough to satisfy the customer’s needs.

If the returning load is decreased, this indicates that either the delivery decreased, the consumption increased, or both.

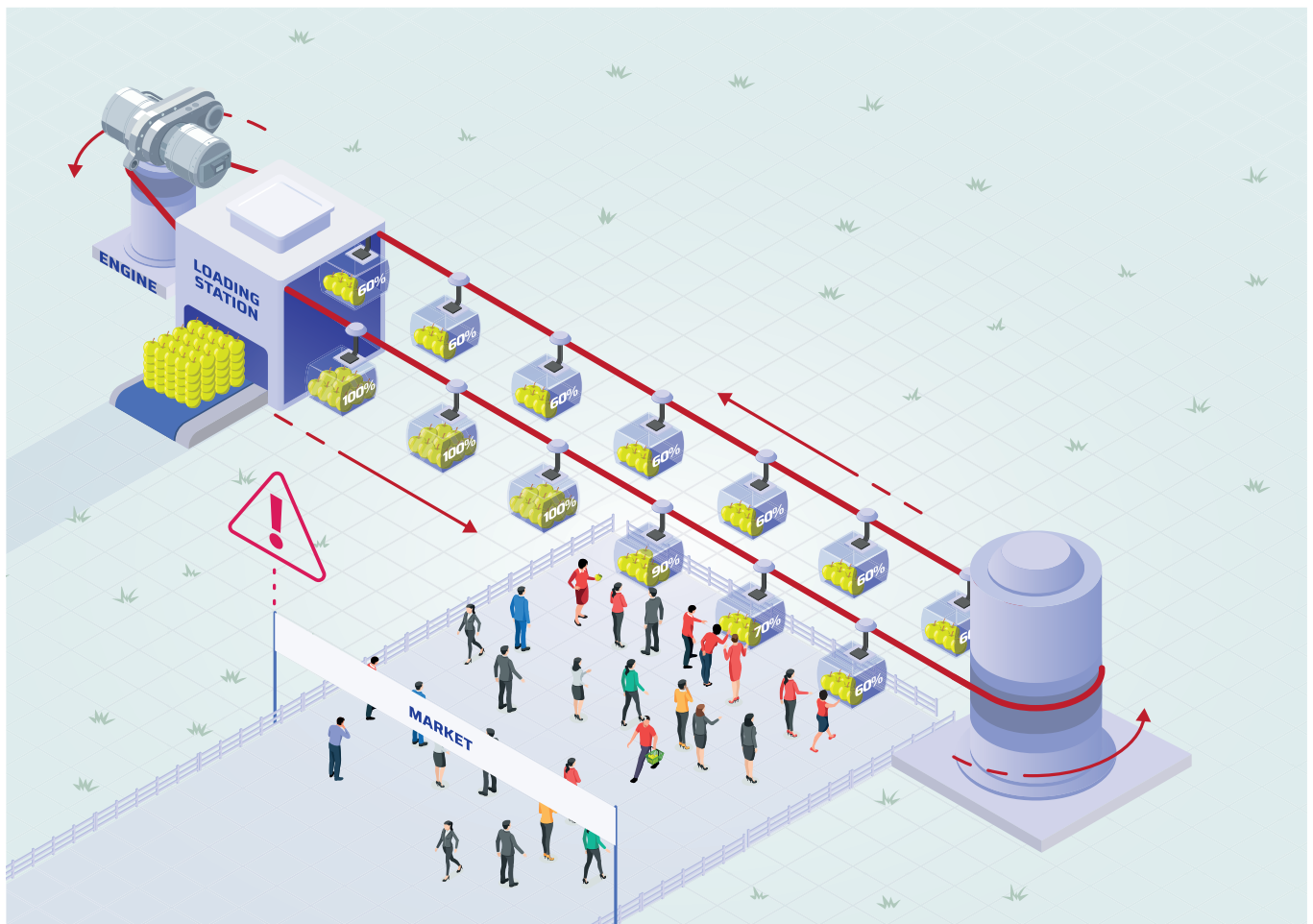


FIGURE 2 - Increased demand. (i.e. increased oxygen consumption in the tissues)

Actual human physiology

Apple ropeway metaphor

Physical exercise (Fig. 2)

During physical exercise, the oxygen consumption increases, so that the mixed venous return would decrease. In response, the cardiac output is increased so that tissue perfusion is increased and $ScvO_2$ remains stable, around 70 %

At some point, the demand of the customers increases. They eat more apples while the cabin passes through the store: the cabins would return to the loading station filled with 50-60% of their loading capacity. In response, the control center will increase the power to the engine and hence the speed of the rope (cardiac output) so that more cabins are sent to the periphery in a given amount of time. Hence, the returning cabins will be filled again with a 70 % of their loading capacity.



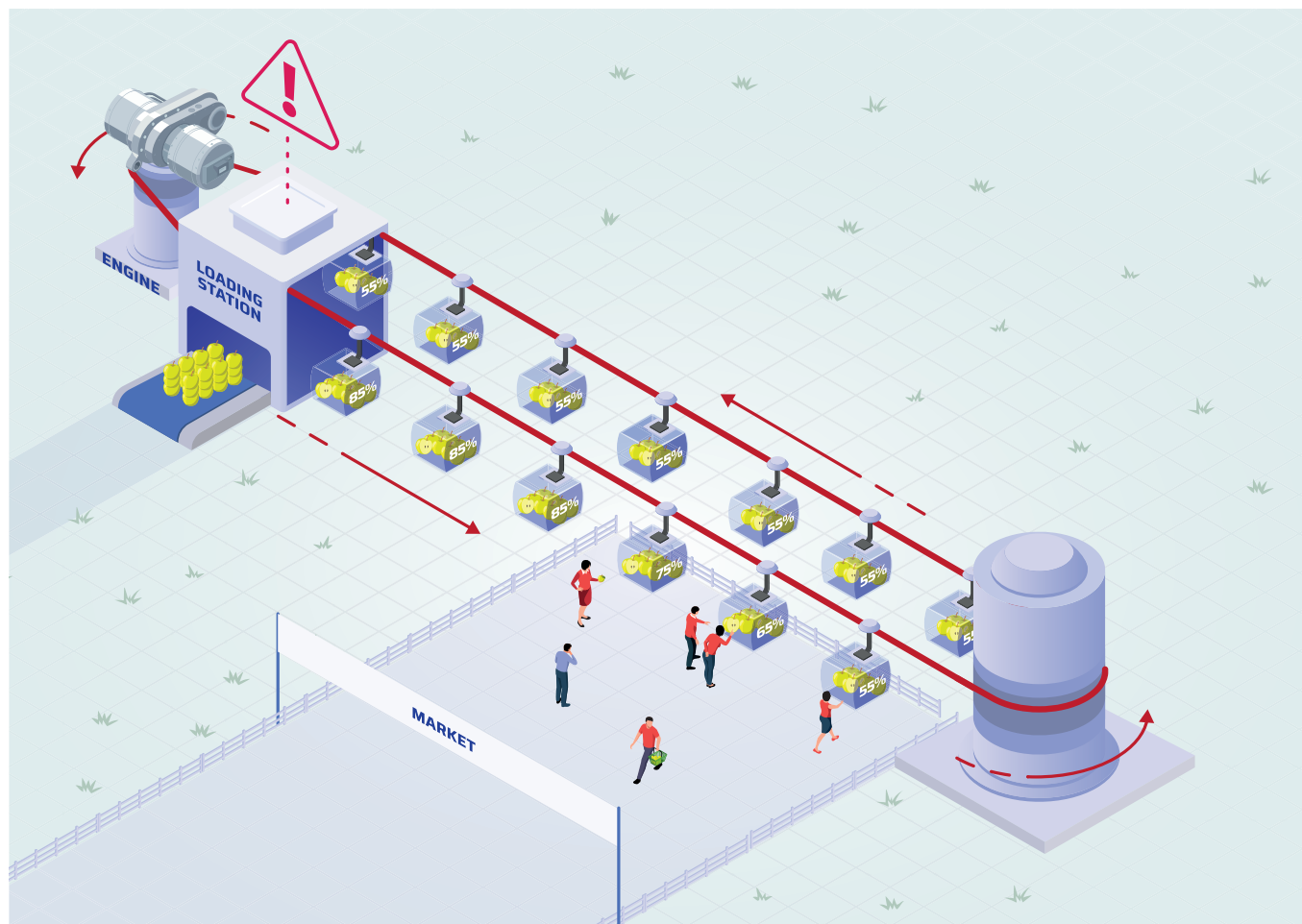


FIGURE 3 - Reduced arterial saturation.

| Actual human physiology | Apple ropeway metaphor |
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| Arterial hypoxaemia (Fig. 3) | |
| <p>In some circumstances, the Partial pressure of oxygen in the capillary drops, so that hemoglobin saturation decreases. In order to keep the DO_2 constant, it is possible to acutely increase the Cardiac Output, but this is inefficient in the long term.</p> <p>Hence, when hypoxaemia is chronic (e.g., high altitude exposure, COPD), hemoglobin concentration rises (6).</p> | <p>In some circumstances, the height of the stack of apples cannot be raised above a given value due to the malfunctioning of the loading system: in order to keep the apples delivery constant in acute conditions, it is possible to increase, transiently, the speed of the rope, but this is inefficient in the long term.</p> <p>Hence, when this happens over a long period of time (chronic conditions), it is more efficient to increase the number of cabins along the wire (polycythemia).</p> |
| Diffusion Limitation | |
| <p>Oxygen diffusion from the alveolar space to the blood is impaired, so that the capillary transit time might not allow a full saturation of hemoglobin</p> | <p>The system of loading the apples on the cabins becomes less efficient, so that the transit time in the loading station is insufficient to allow a full loading of the cabin: they leave to the periphery partially unloaded.</p> |



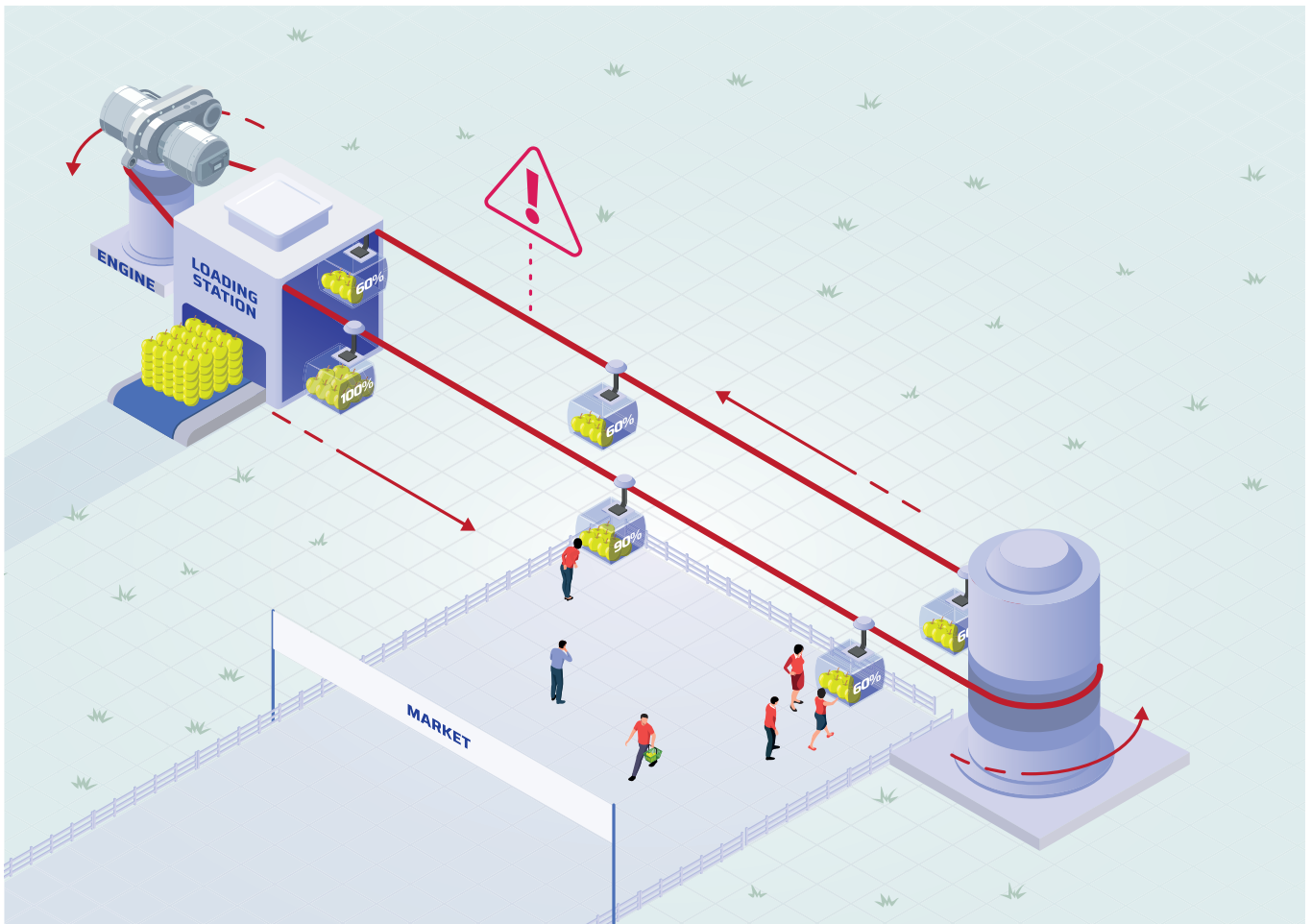


FIGURE 4 - Fewer cabins.

| Actual human physiology | Apple ropeway metaphor |
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| Anemia (Fig. 4) | For a given number of reasons, the number of cabins is decreased, and under normal circumstances, the number of apples reaching the store is very small. Customers eat a large fraction of the apples in the cabins, which return to the loading station with a very low loading. The speed of the rope must be increased to compensate for this. |
| Carbon monoxide intoxication | Carbon Monoxide (CO) binds hemoglobin with an affinity much greater than oxygen, which then cannot bind to hemoglobin. The tissue will suffer from a low DO_2 . An unfair competitor loaded most cabins with rotten apples. There is no room for good apples: customers will suffer for lack of good apples, but at the same time, there is no way of getting rotten apples out of the cabins. |
| Metformin intoxication | Metformin (a common anti-diabetic drug) intoxication causes the inhibition of mitochondrial respiration, so that tissues are unable to consume oxygen, but energy production occurs only via anaerobic lactate generation. As a consequence, the global VO_2 is greatly reduced, and $ScvO_2$ is abnormally elevated (7) despite a severe lack of energy peripheral production. Customers in the market are almost unable to reach out for the apples and eat them. As a consequence, they starve, but the cabins returning to the leading station are almost (90%) full. |

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| Actual human physiology | Apple ropeway metaphor |
|---|--|
| Shock | |
| The circulatory system is deranged either due to a cardiac failure (cardiogenic shock) or to a loss of vascular tone (maldistributive shock) (8). Hemoglobin concentration and saturation may be normal, but cardiac output is reduced, so that DO ₂ drops, becoming adequate relative to tissue consumption, which may become hypoxemic. The vessel needs to regain tone, and/or the heart function must be improved! | The system moving the rope becomes inefficient: the engine loses power and/or the rope loses tension. The number of cabins along the rope and their ability to carry apples are the same, but the rope runs more slowly, so that the delivery of the apples to the store is decreased, and some customers may not have enough apples to eat. The rope needs to be tightened, and/or the engine restored! |

In summary, we provide a visual description in “lay terms” of the principles regulating oxygen transportation to and from peripheral tissues, extraction and monitoring of these processes. Despite some simplification, the apple ropeway metaphor quite accurately resembles this process (and even more examples could be drawn!), and we hope it might help younger clinicians in approaching this fascinating and crucial topic.

Disclosures

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