BioFlow: Fish-Gill Inspired Oxygen Patch

Introduction

Oxygen is essential for survival, but in many medical emergencies the body cannot receive oxygen fast enough. Current oxygen delivery methods often rely on bulky equipment or invasive procedures, making them difficult to use in emergency or remote situations. This creates a need for a faster, safer, and more accessible way to deliver oxygen.

BioFlow: Fish-Gill Inspired Oxygen Patch (referred to as **BioFlow Patch**) explores a nature-inspired solution to this problem. By learning from how animals efficiently absorb oxygen, this project proposes a non-invasive oxygen patch designed to improve emergency oxygen delivery. The BioFlow Patch aims to make oxygen support simpler, safer, and more accessible when it is needed most.

Present Technology

Currently, oxygen is delivered using methods such as oxygen tanks, masks, nasal cannulas, and ventilators. More recently, researchers at Boston Children's Hospital have developed **injectable oxygen foams** that contain oxygen-filled microbubbles designed to deliver oxygen directly into the bloodstream (Kheir et al., 2012; Mancebo et al., 2024). In animal studies, these oxygen foams helped maintain blood oxygen levels during severe oxygen deprivation, including conditions such as cardiac arrest and respiratory failure (Kheir et al., 2012).

Scientific Principles:

- The foam works because oxygen dissolves from the microbubbles into the blood, where hemoglobin transports it to organs throughout the body (Guyton & Hall, 2021).
- Blood circulation then delivers oxygen to vital organs such as the brain and heart (Guyton & Hall, 2021).

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- This process relies on diffusion, where oxygen moves from an area of high concentration (inside the foam bubbles) to an area of lower concentration (the surrounding blood) (Feder & Burggren, 1985).

Limitations / Problems:

- **Invasive:** The oxygen foam must be injected into veins, requiring trained medical personnel and sterile conditions (Kheir et al., 2012).
- **Safety concerns:** Injecting gas into the bloodstream can cause blockages known as embolisms, which may interfere with blood flow and pose serious health risks (Knox, 2012).
- **Short duration:** The oxygen is released rapidly and is difficult to control, limiting its effectiveness for longer-term oxygen support (Kheir et al., 2012).
- **Accessibility:** Because the foam requires injection, it is not easily used outside hospitals, ambulances, or controlled medical environments (Mancebo et al., 2024).

While Boston Children's Hospital's oxygen foam is a promising medical advancement, its reliance on injection, short duration, and safety risks highlights the need for a safer, non-invasive delivery system that still provides rapid oxygen support.

History of Oxygen Use in Medicine

- **1774 – Discovery of Oxygen**: Oxygen was discovered by Joseph Priestley, who identified it as a gas essential for combustion and life. This discovery laid the foundation for understanding the role of oxygen in human health and medicine (Priestley, 1775).
- **Late 1700s–Early 1800s – Early Medical Experiments**: Following its discovery, scientists and physicians began experimenting with oxygen to treat breathing problems.

However, medical knowledge of respiratory physiology was limited, and equipment for delivering oxygen was unreliable and difficult to control (West, 2012).

- **1840s–1860s – Early Hospital Use**: Oxygen began to be used occasionally in hospitals for patients with lung diseases. Delivery systems were large, inefficient, and inconsistent, which limited oxygen therapy to a small number of cases (West, 2012).
- **Early 1900s (1900–1920) – Oxygen Tanks and Masks**: Compressed oxygen tanks and face masks were introduced, making oxygen therapy more practical and widespread in hospitals. This marked the beginning of standardized oxygen treatment in clinical settings (West, 2012).
- **1940s–1950s – Mechanical Ventilators**: Mechanical ventilators were developed to support patients who could not breathe on their own. Oxygen therapy became a standard medical treatment for respiratory failure, surgery, and critical care (Slutsky, 2015).
- **1970s–1980s – Improved Oxygen Delivery Systems**: Nasal cannulas, improved oxygen masks, and centralized hospital oxygen systems were refined. These advancements made oxygen delivery safer, more comfortable, and easier to control for patients (West, 2012).
- **1990s–2000s – Portable Oxygen Concentrators**: Portable oxygen concentrators were developed, allowing patients to receive oxygen outside hospital settings. While these devices increased mobility, they still relied on electricity and remained bulky and expensive (Croxton & Bailey, 2006).
- **2020s – Injectable Oxygen Foams:** Researchers at Boston Children's Hospital developed oxygen-rich injectable foams that deliver oxygen directly into the bloodstream. Animal studies demonstrated improved survival during severe oxygen deprivation, such as cardiac arrest or respiratory failure (Kheir et al., 2012; Mancebo et

al., 2024). However, these foams are invasive, carry safety risks, and require trained medical professionals, highlighting the need for safer and more accessible oxygen delivery methods (Mancebo et al., 2024).

Despite more than 200 years of advancements, oxygen delivery still relies primarily on pushing oxygen into the lungs or bloodstream using invasive or bulky technologies. This history shows a clear need for innovative, safer, and non-invasive oxygen delivery methods that can provide rapid support in emergencies. The BioFlow Fish-Gill Inspired Oxygen Patch aims to address this need.

Future Technology

In the future, we envision the BioFlow Patch, a wearable oxygen delivery system designed to provide rapid, non-invasive oxygen support during medical emergencies. Instead of injecting oxygen directly into the bloodstream, the patch uses oxygen-rich foam developed by researchers at Boston Children's Hospital, which is placed on the skin over areas with high blood flow, such as the upper chest, neck, or inner arm (Kheir et al., 2012; Mancebo et al., 2024).

The patch is inspired by fish gills and contains microchannels and sponge-like layers that increase surface area (Perry, 2024). This design allows oxygen from the foam to contact the skin over a wide area, improving absorption efficiency through diffusion.

The BioFlow Patch would be made using a medical-grade silicone resin that is safe for prolonged skin contact and can be 3D printed using existing technology. Medical-grade silicone resins meet international safety standards for skin biocompatibility and are widely used in wearable medical devices (ISO 10993; Wagner et al., 2020). This flexible silicone allows the fish-gill-inspired microchannels to be printed precisely and comfortably for the user. Because this material already exists and is compatible with commercial stereolithography (SLA) printers, no future breakthrough in materials is required for the design.

The main invention is the Fish-Gill patch, which acts as a controlled oxygen reservoir. The oxygen foam is held safely inside the patch and gradually releases oxygen into the body, making it safer and easier to use than injections or traditional oxygen tanks.

Scientific Principles

1. **Diffusion (Frog Skin Principle)**: Oxygen naturally moves from areas of high concentration (the foam in the patch) to areas of lower concentration (blood in nearby capillaries). This is the same principle that allows amphibians like frogs to absorb oxygen directly through their skin (Boutilier et al., 1992; Feder & Burggren, 1985).
2. **Capillary Placement (Human Adaptation)**: To make diffusion work in humans, the patch is placed over areas with dense capillary networks (Guyton & Hall, 2021). Capillaries lie close to the skin surface, allowing oxygen to enter the bloodstream efficiently (Guyton & Hall, 2021).
3. **Surface Area Maximization (Fish Gills Principle)**: Microchannels in the patch mimic fish gills, which use thin membranes and large surface areas to absorb oxygen from water (Perry, 2024; Evans et al., 2005). These channels maximize contact between oxygen and skin, improving diffusion (Evans et al., 2005).

Advantages Over Existing Technology

- **Non-invasive:** No needles, no risk of embolism.
- **Portable:** Can be worn anywhere, including in ambulances, disaster zones, or remote locations.

- **Controlled oxygen delivery:** Diffusion through the patch allows oxygen to enter the bloodstream gradually rather than all at once.
- **Rapid action:** Oxygen reaches vital organs like the brain and heart through capillaries within minutes.
- **Nature-inspired efficiency:** Combines proven diffusion and surface-area principles from animals for safe and effective oxygen delivery.

Breakthroughs

Why This Future Technology Does Not Exist Today: Even though Boston Children's Hospital's injectable oxygen foam works well, there is currently no way to deliver it safely through the skin in humans (Kheir et al., 2012). The challenge is designing a patch that:

1. Holds the foam securely,
2. Allows controlled oxygen diffusion into capillaries, and
3. Maximizes absorption using a fish-gill-inspired structure.

These requirements explain why oxygen delivery is still invasive today.

Required Breakthrough: The key breakthrough for the BioFlow Patch is the fish-gill-inspired microchannel design, which:

- Increases surface area to maximize oxygen diffusion,
- Holds the foam safely, and
- Guides oxygen toward capillaries for rapid uptake.

Proposed Investigation

Purpose: To test whether a single fish-gill-inspired patch can efficiently deliver oxygen into a simulated blood system.

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Research Question: Can the fish-gill-inspired patch deliver oxygen faster and more efficiently than a flat patch design?

Hypothesis: The fish-gill-inspired patch will increase oxygen diffusion rate compared to a flat patch, because the microchannels increase surface area and contact with the skin.

Materials:

- Fish-gill-inspired oxygen patch (made from 3D-printable medical-grade silicone-based material that has passed safety tests)
- Oxygen foam
- Simulated blood solution or oxygen-absorbing fluid
- Transparent test chamber
- Oxygen sensors or dissolved oxygen probes
- Timer
- Temperature-controlled environment

Procedure:

1. Place the simulated blood solution in a sealed test chamber.
2. Place the fish-gill-inspired patch on top of the chamber with oxygen foam inside.
3. Begin timing and measure oxygen concentration in the simulated blood every 30 seconds for 10–20 minutes.
4. Compare results to a flat patch control to measure the effect of the fish-gill microchannels.
5. Keep temperature and oxygen source constant for all trials.

Data and Measurements Collected:

- Oxygen concentration in the simulated blood over time (% saturation or mg/L)
- Rate of oxygen diffusion (slope of concentration vs. time)

- Total oxygen absorbed after 10–20 minutes
- Comparison of fish-gill patch vs. flat patch

Data Analysis:

- Graph oxygen concentration vs. time for each patch.
- Determine whether the microchannel design increases diffusion efficiency.
- Confirm that oxygen enters the system gradually, not in bursts, showing controlled delivery.

Expected Results:

- The fish-gill patch should allow faster, more uniform oxygen diffusion than a flat patch.
- Oxygen delivery should be safe, gradual, and sufficient to maintain levels in simulated blood.

Safety and Ethics Considerations:

- No humans or animals are used; all tests are done in a simulated system.
- Oxygen levels are kept within safe laboratory limits.
- Biocompatible materials have been pre-tested, so no new toxicity testing is required at this stage.

Design Process

During the design of the BioFlow Fish-Gill Inspired Oxygen Patch, our team explored several alternative ideas before selecting the final design. Each option was evaluated based on safety, feasibility, accessibility, and effectiveness during medical emergencies.

Alternative Idea 1: Injectable Oxygen Foam with AI-Controlled Release

- **Description:** The first idea involved improving existing injectable oxygen foam by adding artificial intelligence (AI) to control when and where oxygen is released in the body. The foam's oxygen microbubbles would be designed to release oxygen only near vital organs such as the brain or heart.

- **Why It Was Rejected:** Although injectable oxygen foam has shown success in animal studies, it must still be injected directly into the bloodstream, making it invasive and requiring trained medical personnel. There are also safety concerns related to gas bubbles in blood vessels, including the risk of blockages. Adding AI-controlled release would increase complexity, cost, and technical challenges, and such systems do not currently exist for safe human use.
- **Why BioFlow Is Better:** The BioFlow patch eliminates injections entirely. Oxygen is delivered through natural diffusion across the skin, making it safer, simpler, and easier to use in emergency or remote settings.

Alternative Idea 2: Oxygen Patch Inspired by Other Animal Systems

- **Description:** The team considered designing the patch based on other biological oxygen systems, such as insect tracheal tubes or mammalian lung structures.
- **Why It Was Rejected:** Insect respiratory systems rely on internal air tubes that are not compatible with human anatomy. Mammalian lung structures are highly complex and function only inside the body, making them unsuitable for a wearable external device.
- **Why BioFlow Is Better:** Fish gills are specifically designed for oxygen exchange across thin membranes with large surface areas. This structure can be realistically mimicked in a flat, wearable patch, making it the most practical biological model for non-invasive oxygen delivery.

Alternative Idea 3: Nasal Absorption of Oxygen Foam

- **Description:** Another idea was to deliver oxygen foam through the nose, allowing oxygen to be absorbed through nasal tissues instead of through the skin.
- **Why It Was Rejected:** The nasal passages are sensitive and easily irritated. Introducing oxygen foam could block airflow, interfere with breathing, or cause discomfort. Oxygen absorption through nasal tissue is also limited and difficult to control safely.
- **Why BioFlow Is Better:** Skin-based delivery provides a larger and more stable surface area. When placed over areas with dense capillary networks, the BioFlow patch allows oxygen to diffuse safely and gradually into the bloodstream without affecting breathing.

Final Design Choice: After evaluating these alternatives, the team selected the BioFlow Fish-Gill Inspired Oxygen Patch. This design combines existing oxygen foam technology with a fish-gill-inspired microchannel structure and a medical-grade silicone patch. The result is a non-invasive, portable, and controlled oxygen delivery system that is safer and more practical than the rejected designs.

Consequences

Type	Positive Consequences	Negative Consequences / Challenges
Medical	Rapid oxygen delivery in emergencies (asthma attacks, heart attacks, hypoxia) (Guyton & Hall, 2021).	Oxygen diffusion depends on blood circulation; in patients with poor circulation, shock, or severe vascular disease, oxygen transfer may be reduced (Guyton & Hall, 2021).

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Type	Positive Consequences	Negative Consequences / Challenges
Safety	Non-invasive: eliminates risk of blood embolism/infections from injections (Kheir et al., 2012).	Skin irritation or allergic reactions possible in some users (Ratner et al., 2020).
Accessibility	Portable and easy to use in ambulances, remote areas, or disaster zones.	May not deliver enough oxygen for extremely severe cases without multiple patches.
Societal / Lifestyle	Could save lives outside hospitals, reduce strain on emergency services.	Users may rely on patch instead of seeking full medical care in serious cases.
Environmental / Manufacturing	Made from medical-grade silicone resin, which is safe, durable, 3D-printable, and can be recycled after use (ISO 10993; Ratner et al., 2020).	Silicone is not biodegradable, so single-use patches must still be collected and recycled responsibly to reduce environmental impact.
Innovation / Science	Demonstrates nature-inspired biomimicry, could inspire other medical devices.	Development requires advanced materials and testing; may take years to implement.

Societal Impact Summary: On a societal level, the BioFlow Patch could improve emergency survival rates, especially in rural, remote, or disaster-affected communities where hospital care is delayed. By providing immediate oxygen support, it may reduce healthcare system overload during emergencies. However, public education would be necessary to ensure the patch is used as a temporary aid and not a replacement for professional medical care.

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