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Human-Machine Interface Design of Portable Kidney Perfusion System Based on Ergonomics

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Abstract: Aiming at the high cognitive load and operational risks of portable kidney perfusion systems in mobile emergency scenarios, this paper proposes a set of human-machine interface design strategies for portable scenarios based on ergonomic theories. By analyzing key interaction nodes in the whole kidney perfusion workflow, physiological and cognitive characteristics of users, as well as physical and environmental constraints under portable conditions, the design is carried out from three dimensions: interface layout, interactive feedback, and visual display. This paper focuses on the layout of control elements within the reach range of single-hand operation, the perceptual priority design of multimodal abnormal alarms, and the adaptive visualization mapping method for complex perfusion parameters under strong and weak light environments. It aims to reduce operation error rates, improve task execution efficiency and system safety, and provide references for the human-machine interface design of portable similar life support equipment.

Keywords: Portable kidney perfusion; Human-Machine Interface; Ergonomics; Anti-Misoperation Design; Multimodal Interaction; Visual Coding

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1. Introduction

Kidney perfusion is a critical link in organ preservation and transplantation. Traditional perfusion equipment is bulky and complicated to operate, making it difficult to meet the demands of rapid deployment in out-of-hospital emergency treatment, transportation, and field medical scenarios. The research and development of portable kidney perfusion systems breaks scenario restrictions, yet their human-machine interface design faces severe challenges: limited physical dimensions narrow the space for information presentation and operation; environmental factors such as movement and strong light increase operators' cognitive load and the risk of misoperation. As a discipline focusing on optimizing human-machine-environment systems, ergonomics provides a systematic solution framework for this problem [1]. Starting from multi-dimensional constraints of users, tasks, and environments, this paper puts forward a human-machine interface design scheme for portable perfusion systems oriented to safety, efficiency, and intuitiveness.

2. Analysis of design requirements

2.1. Workflow and interface interaction nodes of kidney perfusion

The main workflow of kidney perfusion includes five links: equipment self-inspection, parameter presetting, vascular cannulation connection, perfusion operation monitoring, and perfusion termination judgment, with one important interface interaction node in each link. In the self-inspection stage, the interface shall clearly display the status of sensors, pipeline airtightness and batteries, and block operations, and give specific prompts once abnormalities occur. For parameter presetting, indicators such as target flow rate and pressure shall be quickly and accurately set according to donor kidney types and perfusion schemes. The perfusion operation stage contains the densest information; operators need to keep track of dynamic parameters including renal artery resistance index, perfusion flow rate, perfusate temperature, and bubble detection, and make timely judgments [2].

2.2. Characteristics and operational demands of user groups

The main users of this system are organ procurement coordinators and transplant surgeons, who possess distinctive characteristics and operational requirements. Users generally have abundant medical knowledge but no expertise in equipment engineering, so clinical professional terms shall be adopted on the interface instead of forming technical black boxes. During time-critical organ procurement procedures, users focus their full attention on patients and surgical fields rather than the machine [3]. Therefore, the core operational demands are “recognizable at a glance” and “operable by blind touch”. The former requires the interface to convey core system status within an extremely short visual recognition time; the latter demands physical knobs and touch areas that can be accurately located by muscle memory without continuous visual attention.

2.3. Human-machine constraints under portable scenarios

Portable application environments impose strict physical, environmental, and physiological restrictions on the system’s human-machine interface. Physically, the equipment is designed to be hand-held or back-carried, so screen size is limited, and information presentation must be concise instead of directly copying desktop interfaces. Environmental constraints are complicated: random vibration and jolts during transportation severely interfere with fine hand movements and sharply raise the probability of touchscreen misoperation; illumination varies from extremely dim to strong outdoors and in ambulances, requiring the screen to maintain readability at all times.

3. Human-machine interface layout design

3.1. Zoning of key information and visual hierarchy

The interface layout is arranged according to the priority of information, with the screen divided into three sections: the status alert zone, the core parameter zone, and the auxiliary function zone. The top status alert zone is a long strip spanning the entire screen, featuring icons for perfusion timing, battery level, pipeline connection status, and other indicators. It remains displayed at the top edge of the screen so that the top-level system status can be monitored around the clock. The core parameter zone in the central golden viewing area occupies the largest display space, where the three most critical dynamic indicators, including renal artery perfusion pressure, real-time flow rate, and perfusate temperature, are arranged sequentially in bold and highlighted fonts for excellent recognizability at typical viewing distances. The bottom auxiliary function zone houses folded entrances for infrequent operations such as device settings. This well-structured zoning approach leverages differences in size, position, and color to deliberately guide the user's visual flow in line with task logic, effectively preventing unstructured searches for non-critical information caused by time pressure.

3.2. Control layout and single-hand reach range

For major single-hand operation scenarios of portable equipment, all high-frequency interactive controls are arranged in the thumb's most active area when holding the device. Taking the midline of the screen bottom as the origin, an arc fan-shaped area extends to both sides, where three main physical shortcut keys for perfusion start/pause and alarm mute & parameter confirmation are placed. Users can naturally touch these buttons with thumb pulp without adjusting hand postures. Instead of traditional top tab bars, virtual touch controls adopt bottom radial menus combined with sliding gestures in the middle, integrating force feedback and visual prompts to form thumb muscle memory [4].

3.3. Anti-misoperation and fault-tolerant design for mobile environments

Vibration and impact during transportation are the main causes of misoperation. Protection mechanisms are established in both hardware form and software logic. In hardware design, a continuous 3-millimeter raised flange around the touch screen serves as physical support for the thumb or tiger's mouth, blocking unintended touches outside the effective touch area. In software logic, single taps are replaced by three-step operations of press-slide-release for critical commands such as perfusion start/stop; the sliding distance during decision-making naturally forms an anti-shake threshold. Besides, a 5-second undo floating window is added for all non-fatal parameter modifications [5]. The system's built-in abnormal input filter identifies and eliminates instantaneous large-area unintentional touches caused by vibration according to touch point area and duration characteristics, ensuring clean and reliable instruction streams.

4. Interaction mode and feedback design

4.1. Selection and matching of multimodal interaction channels

To adapt to the feature of split attention at emergency rescue scenes, a comprehensive interactive channel integrating three perception modalities, including vision, audition, and tactile sensation, is constructed. The visual channel is mainly applied to present precise data, such as continuous and detailed information like perfusion pressure waveforms. The auditory channel serves as the priority option for alarms and progress prompts owing to its omnidirectional and compulsory perception advantages; prompt tones with distinct frequencies and rhythms are adopted to differentiate routine events, including operation confirmation, process milestones, and system readiness, so as to form an unobtrusive acoustic background [6]. The tactile channel acts as a vital supplement in privacy-sensitive scenarios or high-noise environments. Vibration motors distributed on different parts of the device generate characteristic vibration patterns: a single short vibration indicates confirmation, a long vibration denotes an error, and vibration pulse groups signal the start or end of perfusion. Such design enables accurate situational awareness of equipment status via tactile perception even when the operator's line of sight is diverted from the screen [7].

4.2. Operation guidance and status prompt mechanism

System operation guidance adopts progressive disclosure without information accumulation. The initial interface only displays main perfusion parameters and a highlighted start button. After pressing, lights and dynamic arrows guide users to connect pressure sensors and pipelines step by step, transforming paper standard operating procedures into tangible interactive guides. During perfusion, a non-intrusive status color system and breathing light pulse effect simulate healthy perfusion rhythms, enabling users to perceive the system's "physiological rhythm" without checking values [8]. When parameters approach but do not reach alarm thresholds, numbers gradually shift from green to yellow, then orange, with slight flashing. This weak warning mode keeps operators semi-alert without triggering stress interference caused by sudden loud alarms.

4.3. Perceptual priority design for abnormal alarms

A strict three-level sensory priority order is established based on the urgency of risks and potential harm to patients. The highest-level red emergency alert is triggered when severe conditions threatening the survival of the transplanted kidney occur, such as a sharp drop in perfusion pressure, air bubbles in the pipeline, or flow interruption. Upon activation, three sensory channels are saturated simultaneously: high-decibel pulsed alarms sound immediately, the entire screen turns red and flashes, and the equipment vibrates intensely, ensuring the alert will not be overlooked amid noisy surroundings. The secondary yellow alert, for instances like abnormal temperature, adopts intermittent audio paired with localized yellow light for notification. The lowest-level gray prompt only displays visual icons to indicate non-clinical warnings such as equipment maintenance [9].

5. Visual display and information presentation

5.1. Visualization mapping of real-time perfusion parameters

Instead of directly showing abstract figures, metaphor-based morphological visualization is adopted for high-order dynamic parameters such as renal resistance index and flow trends. Perfusion flow is presented as dynamic bar waveforms similar to audio equalizers; the fluctuation and stability of bars directly reflect pulse characteristics in renal arteries, and abnormal jagged or flat waveforms can be detected within seconds, far faster than tracking changing numerical values [10]. Trend curves of perfusion pressure and flow are drawn in real time with different colored lines and semi-transparent historical tracks to provide time context. The renal icon color gradient indicates perfusion completion. Such morphological expression converts complex physiological mechanisms into intuitive visual inference, greatly shortening the cognitive chain from data perception to clinical decisions.

5.2. Interface color coding and symbol recognizability

The color and symbol system complies with international medical equipment safety standards and takes red-green color blind users into consideration. The interface adopts dark, low-reflection backgrounds to reduce stray light outdoors and maximize contrast for highlighted alarm colors. Red stands for emergency alarms and irreversible operations; green for normal perfusion and safe connections; orange for early warnings. Linear, high-contrast medical universal symbols and bold sans-serif fonts are used for key renal artery pressure and flow icons [11]. For users with color vision deficiency, shape cues are added to critical alarm icons: triangular icons with exclamation marks for red emergencies and rhombuses for yellow warnings to convey information accurately without color cues [12].

5.3. Illumination adaptation and interface self-adjustment

An ambient light sensor and screen adaptive adjustment module are integrated to cope with drastic light changes, adjusting both brightness and contrast. When the sensor detects a shift from dim rooms to direct sunlight, the screen switches to daylight mode instead of merely boosting backlight: the background turns pure black, key data lines thicken with saturated colors and white outline strokes to strengthen edge contrast. In dark environments, ultra-dark mode automatically activates with drastically reduced screen brightness and dimmed non-informative glow to protect users' dark adaptation vision. All mode transitions adopt microsecond-level smooth fading instead of sudden light shifts to avoid temporary visual interruption and maintain continuous visual judgment [13,14].

6. Conclusion

From an ergonomic perspective, this paper constructs a complete design framework for the human-machine interface of portable kidney perfusion systems. Faced with narrow physical space, dynamic postures, and harsh light environments, it establishes information architecture based on task hierarchy, arranges interactive layouts according to single-hand reach ranges, realizes multimodal feedback through integrated visual, auditory, and tactile senses, and adopts intelligent ambient perception to achieve adaptive visual design. The scheme effectively meets high requirements for operation safety and cognitive fluency in mobile clinical scenarios [15]. This design idea provides an ergonomic solution for miniaturization and intellectualization of kidney perfusion equipment, and its methodology can be extended to improve human-machine interaction of portable life support devices including extracorporeal membrane oxygenation (ECMO) and emergency transfusion equipment, possessing important clinical transformation significance and universal design enlightenment value.

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