



OPEN Readiness for remote healthcare and artificial intelligence in kidney transplant care: a cross-sectional study

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Kidney transplant patients require intensive follow-up, including monitoring of immunosuppression and screening for complications. Information and communication technologies (ICT) and artificial intelligence (AI) may help optimize and personalize transplant care. We assessed patients' attitudes toward these technologies using a structured questionnaire. A total of 130 patients participated, including 82 (63.1%) kidney transplant recipients and 48 (36.9%) patients awaiting transplantation. Smartphone (96.9%) and computer (93.8%) ownership was high. Most participants perceived ICT as improving the quality of care (81.7%). AI was primarily viewed as a supportive tool for physicians (59.8%), although many participants expressed doubts regarding its medical (50.4%) and social capabilities (61.2%). In multivariable analyses, higher education was independently associated with greater willingness to share health data via a clinic app (adjusted OR 3.73, 95% CI 1.57–8.89) and better comprehension of AI (adjusted OR 5.35, 95% CI 2.23–12.79). Higher eHealth literacy was associated with greater acceptance of online communication (adjusted OR 1.11, 95% CI 1.02–1.21) and better comprehension of AI (adjusted OR 1.11, 95% CI 1.03–1.20), while male sex was associated with greater trust in AI-generated treatment plans (adjusted OR 2.55, 95% CI 1.14–5.69). These findings support the integration of ICT and AI into transplant care while highlighting the need for targeted implementation strategies tailored to specific patient groups.

Keywords Kidney transplantation, Artificial intelligence, Digital health, eHealth, Telemedicine, Patient engagement

Recipients of kidney transplants face specific medical challenges, including the need for lifelong immunosuppressive therapy, regular follow-up examinations, and close monitoring for potential complications.¹ The complexity of care usually requires coordinated collaboration between various healthcare providers, such as transplant centers, nephrologists in private practice and general practitioners.² In the first year after transplantation, patients attend an average of 14 nephrological follow-up appointments, not including any other necessary doctor's visits.³ Given the large number of doctor-patient contacts, effective and patient-centered communication is essential to ensure optimal coordination of care and to empower patients to take responsibility for their own health.⁴ In addition, kidney transplant recipients are at increased risk of infections and immunological and surgical complications.^{5,6} Barrier-free access to timely clinical examinations is therefore crucial to improving long-term overall survival and allograft survival. Modern digital information and communication technologies (ICT) offer considerable potential for overcoming the challenges associated with transplant care. Current developments in this area include mobile health applications, telemedicine procedures, and wearable health monitoring

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systems.^{7,8} Numerous studies have demonstrated various advantages of using ICT in the care of transplant patients, including improved adherence to immunosuppressive therapies, a reduction in hospitalization rates, and a decrease in health-related costs.^{9–11} In particular, digital health interventions such as medication reminder applications, electronic adherence monitoring systems and electronic pillboxes may help improve adherence to immunosuppressive medication, which remains a cornerstone of long-term graft survival.^{12,13} Furthermore, the upcoming integration of artificial intelligence (AI) methods into solid organ transplant medicine has the potential to fundamentally transform the quality of care in this area.^{14,15} Promising applications include AI-assisted pharmacokinetic modelling of immunosuppressive drugs, which may help optimize therapeutic drug monitoring and enable more personalized immunosuppressive treatment.¹⁶ Despite significant advances in the development of digital solutions for healthcare, the use of modern ICT in kidney transplant remains very limited.¹⁷ A recent survey found that around a quarter of British transplant centers do not use digital patient records and continue to work with paper documents.¹⁸ Although there are promising digital approaches, including platform-based ones being used by individual transplant centers, broader implementation in transplant medicine has yet to take place, both in Germany, where the current study was conducted, and in Europe, with regard to the European Health Data Space.¹⁹ Understanding the perspective of transplant patients on this topic is crucial for the successful deployment of modern ICT and for the development of remote healthcare structures in the field of solid organ transplantation. In a previous study, conducted before the COVID-19 pandemic, we showed that transplant patients generally have a positive attitude towards remote healthcare.²⁰ The COVID-19 pandemic has now significantly accelerated the further development and use of digital technologies in the general population.⁸ Nevertheless, there is currently insufficient data and information from patients in the field of transplant medicine that could serve as a basis for the targeted, patient-centered development of digital ICT in solid organ transplantation and that takes into account the possible change in patients' attitudes and perceptions as a result of the coronavirus pandemic. This study aims to close this gap and investigate the current attitudes of transplant patients in order to ensure the best possible and, in particular, patient-oriented further development of remote healthcare in the field of transplant medicine. Digital technologies in transplant care can currently be broadly divided into patient-facing applications and those used in clinical or medical settings. Patient-facing technologies include, for example, mobile health applications and wearables, as well as digital tools for collecting or transmitting health-related data. In contrast, AI applications used by healthcare professionals are intended to support medical decision-making, for example through individualized optimization of immunosuppressive dosing, risk stratification, or the prediction of graft dysfunction and rejection reactions. This questionnaire covered both areas by examining both patients' willingness to use digital technologies in their own care and their attitudes toward the use of AI by healthcare professionals.

Materials and methods

Study population

The study included patients aged ≥ 18 years who presented at the Transplant Center of the University Hospital of Tübingen between June 2023 and November 2024 for outpatient care before or after kidney transplant. During the medical consultation, patients were informed about the voluntary participation in a survey on attitudes towards digital ICT and AI in transplant medicine. In addition, the treating physicians assessed any possible health restrictions that could impair the patient's ability to participate.

Questionnaire

The questionnaire was developed as an exploratory measurement tool by an interdisciplinary team with expertise in transplant medicine, nephrology, general practice, health services research, medical quality management, and behavioral sciences. No formal pilot study, Delphi method, or psychometric validation was conducted. Before the study began, the questionnaire was informally pre-tested with individual patients and subsequently reviewed and revised multiple times by the study team to improve clarity, comprehensibility, and content relevance. In order to assess internal consistency, Cronbach's alpha was calculated for conceptually related multi-item domains of the questionnaire. The questionnaire consisted mainly of closed questions, including Likert scales to assess agreement with standardized statements.

The following topics were covered:

- current use of digital ICT,
- attitudes toward digital health information,
- perspectives on the future use of ICT,
- personal experiences in the context of medical care,
- willingness to use AI in healthcare,
- health-related quality of life (measured using the EQ-5D questionnaire),
- sociodemographic variables (age, gender, educational level, eHealth literacy, type of health insurance, employment status and place of residence).

Although completion time during the pre-testing was not formally recorded, participants typically required approximately 20 min to complete the questionnaire. To minimize potential biases in the selection of the study population that might favor participants with digital literacy, and to enable participation regardless of digital literacy or access to digital devices, the questionnaire was administered exclusively in paper form.

	Total, <i>n</i> (%)	Age group, <i>n</i> (%)		<i>P</i> value	Gender, <i>n</i> (%)		<i>P</i> value
		≤ 53y	> 53y		Male	Female	
Transplant status							
Post-transplant	82 (63.1)	40 (60.6)	42 (65.6)		33 (61.1)	49 (64.5)	
Pre-transplant	48 (36.9)	26 (39.4)	22 (34.4)	n.s. (0.59)	21 (38.9)	27 (35.5)	n.s. (0.72)
On Dialysis	37 (77.1)	20 (76.9)	17 (77.3)		14 (66.7)	23 (85.2)	
Not on dialysis	11 (22.9)	6 (23.1)	5 (22.7)	n.s. (1.00)	7 (33.3)	4 (14.8)	n.s. (0.17)
Post-transplant phase							
Early (< 12 months)	15 (18.3)	9 (22.5)	6 (14.3)		7 (21.2)	8 (16.3)	
Late (≥ 12 months)	67 (81.7)	31 (77.5)	36 (85.7)	n.s. (0.40)	26 (78.8)	41 (83.7)	n.s. (0.58)
Donor type							
Living donor	45 (54.9)	29 (72.5)	16 (38.1)		17 (51.5)	28 (57.1)	
Deceased donor	37 (45.1)	11 (27.5)	26 (61.9)	0.002	16 (48.5)	21 (42.9)	n.s. (0.66)
No. of transplants							
First	69 (84.1)	33 (82.5)	36 (85.7)		27 (81.8)	42 (85.7)	
Second or more	13 (15.9)	7 (17.5)	6 (14.3)	n.s. (0.77)	6 (12.2)	7 (14.3)	n.s. (0.76)
Gender							
Male	52 (40.6)	26 (40.6)	26 (40.6)				
Female	76 (59.4)	38 (59.4)	38 (59.4)	n.s. (1.00)			
ISCED level							
low/medium	72 (55.4)	36 (54.5)	36 (56.3)		33 (63.5)	39 (51.3)	
high	58 (44.6)	30 (45.5)	28 (43.8)	n.s. (0.85)	19 (36.5)	37 (48.7)	n.s. (0.17)
Community Size (inhabitants)							
≤ 30.000	95 (73.1)	43 (65.2)	52 (81.3)		40 (76.9)	54 (71.1)	
> 30.000	35 (26.9)	23 (34.8)	12 (18.8)	0.039	12 (23.1)	22 (28.9)	n.s. (0.46)
eHealth Literacy level							
low/medium	92 (70.8)	44 (66.7)	48 (75.0)		35 (67.3)	56 (73.7)	
high	38 (29.2)	22 (33.3)	16 (25.0)	n.s. (0.30)	17 (32.7)	20 (26.3)	n.s. (0.43)
Insurance							
Statutory	117 (90)	60 (90.9)	57 (89.1)		47 (90.4)	68 (89.5)	
Private	13 (10)	6 (9.1)	7 (10.9)	n.s. (0.73)	5 (9.6)	8 (10.5)	n.s. (0.87)
Profession							
Currently employed	72 (55.4)	48 (72.7)	24 (37.5)		25 (48.1)	45 (59.2)	
No current employment	58 (44.6)	18 (27.3)	40 (62.5)	<0.001	27 (51.9)	31 (40.8)	n.s. (0.21)
Distance to Transplantation Centre							
> 50 km	37 (28.5)	15 (22.7)	22 (34.4)		19 (36.5)	16 (21.1)	
≤ 50 km	93 (71.5)	51 (77.3)	42 (65.6)	n.s. (0.14)	33 (63.5)	60 (78.9)	n.s.(0.054)
Health-related quality of life (EQ-5D)							
<i>Mobility</i>							
No problems	105 (80.5)	57 (86.4)	46 (74.2)		40 (78.4)	61 (81.3)	
Moderate problems	25 (19.5)	9 (13.6)	16 (25.8)		11 (21.6)	14 (18.7)	
Severe problems	0 (0.0)	0 (0.0)	0 (0.0)	n.s. (0.08)	0 (0.0)	0 (0.0)	n.s. (0.67)
<i>Self-care</i>							
No problems	122 (96.1)	61 (93.8)	61 (98.4)		48 (96.0)	72 (96.0)	
Moderate problems	5 (3.9)	4 (6.2)	1 (1.6)		2 (4.0)	3 (4.0)	
Severe problems	0 (0.0)	0 (0.0)	0 (0.0)	n.s. (0.19)	0 (0.0)	0 (0.0)	n.s. (1.00)
<i>Usual activities</i>							
No problems	89 (70.1)	48 (72.7)	41 (67.2)		32 (62.7)	56 (75.7)	
Moderate problems	36 (28.3)	16 (24.2)	20 (22.8)		18 (35.3)	17 (23.0)	
Severe problems	2 (1.6)	2 (3.0)	0 (0.0)	n.s. (0.25)	1 (2.0)	1 (1.4)	n.s. (0.30)
<i>Pain/Discomfort</i>							
No pain	64 (50.0)	35 (53.0)	29 (46.8)		27 (52.9)	36 (48.0)	
Moderate pain	61 (47.7)	30 (45.5)	31 (50.0)		23 (45.1)	37 (49.3)	
Continued							

	Total, <i>n</i> (%)	Age group, <i>n</i> (%)		<i>P</i> value	Gender, <i>n</i> (%)		<i>P</i> value
		≤ 53y	> 53y		Male	Female	
Severe pain	3 (2.3)	1 (1.5)	2 (3.2)	n.s. (0.67)	1 (2.0)	2 (2.7)	n.s. (0.85)
Anxiety							
No anxiety	88 (68.8)	42 (63.6)	46 (74.2)		38 (74.5)	48 (64.0)	
Moderate anxiety	38 (29.7)	24 (36.4)	14 (22.6)		13 (25.5)	25 (33.3)	
Severe anxiety	2 (1.6)	0 (0.0)	2 (3.2)	n.s. (0.10)	0 (0.0)	2 (2.7)	n.s. (0.29)

Table 1. Transplant data, baseline demographic and clinical data of patients included in the study, stratified by age and gender. Data are given as absolute numbers (percent). Statistically significant *P*-values are shown in bold. *n.s.* not significant.

Transplant characteristics

Data on transplant status, time since transplantation, number of previous transplantations, and donor type were retrieved from the patients' electronic health records. For exploratory subgroup analyses, transplant recipients were categorized into an early (< 12 months) and a late (≥ 12 months) post-transplant phase.

Ethics

This study was reviewed and approved by the Ethics Committee of the University Hospital of Tübingen. Written informed consent was obtained from all patients prior to study inclusion. The study was conducted in accordance with the Declaration of Helsinki.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics, version 28.0.0.0 (IBM Corp., Armonk, NY, USA).

Responses on the four-point Likert scale were categorized into positive ("strongly agree" and "agree") and negative ("somewhat disagree" and "disagree") categories to distinguish between general acceptance and non-acceptance and to facilitate the interpretation of the subgroup analyses. Age and eHealth literacy were dichotomized based on their respective median values to obtain balanced comparison groups and ensure a consistent analytical approach across all exploratory subgroup analyses.

With regard to health-insurance, a dichotomization was made between those with statutory health insurance and private health insurance. The level of education was assessed according to the International Standard Classification of Education (ISCED, UNSECO) and summarized in two groups for clarity: ISCED level 2 (lower/middle secondary education) and ISCED level 3 (upper secondary education)²¹.

eHealth literacy, which is defined as "the ability to seek, find, understand, and appraise health information from an electronic source" was assessed using the eHealth Literacy Scale (eHEALS), an internationally validated instrument.^{22,23} This scale comprises eight items for self-assessment, with a possible total score of 8 to 40. Based on established cut-offs, participants with ≤ 32 points were classified as having "low" eHealth literacy and those with > 32 points as having "high" eHealth literacy. Frequency distributions were presented as absolute and relative frequencies (%). Ordinal scaled variables were reported as median with interquartile range (25th /75th percentile).

Decimal values were rounded to one decimal place. Correlations between sociodemographic variables and attitudes towards digital ICT were examined using contingency tables and Pearson's χ^2 tests. Multiple logistic regression analyses were performed to identify independent factors associated with central aspects of digital health and AI acceptance. The dependent variables were selected in accordance with the primary objectives of the study and represented key domains of digital health use and attitudes towards AI. Age, gender, educational level, and eHealth literacy were included as independent variables in all models because they have previously been identified as important determinants of digital health perception. A two-sided *p*-value < 0.05 was considered statistically significant.

Results

Patient characteristics

Overall, 223 patients were invited to participate in the study. Of the 136 patients who agreed to participate, 130 completed the questionnaire. The overall response rate was 58.3% (130/223).

The mean age was 53.0 years (IQR: 40.0–62.3 years). The gender ratio was 1.48:1 (female: male). 82 (63.1%) participants had already received kidney transplantation and 48 (36.9%) were awaiting transplantation. The median time since transplantation in the kidney transplant recipients was 5.1 years (range: 1.8–11.7 years). Among those, 15 (18.3%) were within the first year after transplantation, while 67 (81.7%) were in the late post-transplant phase (≥ 1 year). Detailed demographic and clinical characteristics, including educational level, eHealth literacy, insurance status, employment status, distance of the patient's place of residence from the transplant center, size of place of residence, and health-related quality of life are presented in Table 1, detailed by age group and gender.

Analysis of the internal consistency of selected questionnaire items showed acceptable to high internal consistency across eHEALS items (Cronbach's α = 0.88), items on the acceptance and perceived usefulness of digital healthcare services (Cronbach's α = 0.76), and items assessing the perceived medical capabilities of both physicians (Cronbach's α = 0.96) and artificial intelligence (Cronbach's α = 0.93).

Current use of modern ICT

Most respondents reported owning digital devices with 93.8% ($n=122$) owning a computer and 96.9% ($n=126$) owning a smartphone. Wearables that can be used for automated recording of vital parameters, on the other hand, were used by only 32.3% ($n=42$). The internet was used by 82.3% ($n=107$) for private purposes and by 66.7% ($n=80$) for professional purposes; only 3.9% ($n=5$) stated that they did not use the internet at all. Despite the high availability of modern information systems, 57.4% ($n=74$) continued to document their health-related parameters on paper forms. Blood pressure (90.8%, $n=118$), body weight (86.2%, $n=112$), and urine volume (46.9%, $n=61$) were recorded most frequently on a regular basis.

Subgroup analyses showed significant differences according to age and gender:

- Older participants (>53 years) were less likely to use smartphones (93.8% vs. 100%, $p=0.039$), less likely to have a social media account (39.7% vs. 66.7%, $p=0.002$), and less likely to consider the internet important for their private lives (75.0% vs. 89.4%, $p=0.031$) (Fig. 1). In addition, they documented health data more often on paper (66.7% vs. 48.5%, $p=0.037$) and were less willing to transmit data digitally to doctors (55.6% vs. 74.2%, $p=0.049$) or health insurance companies (38.1% vs. 56.1%, $p=0.005$).
- Men were more likely to report owning wearables (44.2% vs. 25.0%, $p=0.023$) and social media accounts (68.6% vs. 43.4%, $p=0.005$), using therapy apps (30.2% vs. 17.2%, $p=0.027$) and regularly recording health data (46.5% vs. 29.3%, $p=0.03$) (Fig. 1).

Further subgroup-specific results on the use of ICT are shown in Fig. 1.

eHealth literacy

The median eHEALS score in the study population was 30.0 (interquartile range: 24.0–34.0). Higher eHEALS scores were significantly associated with a higher level of education ($p=0.012$). 78.1% ($n=100$) of participants reported feeling confident in their ability to use the internet to search for relevant health information.

When searching online, the most frequently accessed information was about specific diseases (76.0%, $n=95$), side effects of medications (62.1%, $n=77$), and treatments (61.6%, $n=77$), followed by information on nutrition (56.0%, $n=70$) and healthy lifestyle (24.8%, $n=31$).

Participants with higher eHealth literacy searched significantly more often on social media ($p=0.03$) and hospital websites ($p=0.008$). They also rated the exchange of medical data via mobile applications more helpful ($p=0.047$) and showed greater openness to digitally supported forms of care in transplant medicine ($p=0.031$).

Searching for health-related information

Websites created by medical professionals were rated by respondents as both the highest quality source of health-related information (81.7%, $n=85$) and the most frequently used source of information (50.4%, $n=63$).

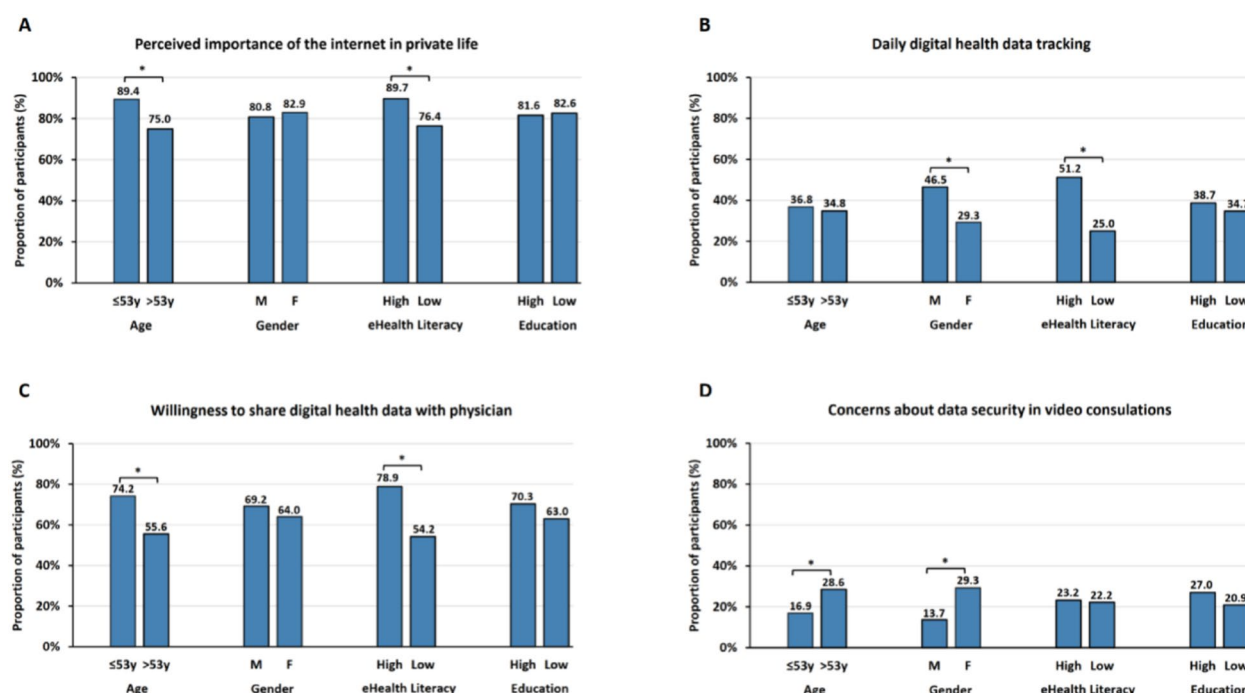


Fig. 1. Perceptions of different aspects of information and communication technologies (ICTs) among kidney transplant patients according to age, gender, eHealth literacy, and education level. The figure shows the proportion of participants who agreed with the respective statement. Differences between subgroups were analyzed using the chi-square test. * P-value ≤ 0.05.

Older patients ($p=0.031$) and participants with lower education ($p=0.039$) reported significantly lower confidence in dealing with online health information. Further results on online searches for health-related information are shown in Fig. 2.

Use of modern ICT for recording and transmitting medical information

Despite the COVID-19 pandemic, the use of modern ICT for recording and transmitting medical or treatment-related information remained low in the study cohort. While the majority of respondents (60.0%, $n=78$) had already made online appointments with their healthcare providers, health messengers were only used by 12.3% ($n=16$), video consultations by 14.6% ($n=19$), digital medication plans by 20.0% ($n=26$), and fitness apps with vital data recording by 17.6% ($n=18$). Higher eHealth literacy was significantly associated with the use of online appointment scheduling ($p=0.041$), and a higher level of education was associated with the use of video consultations ($p=0.001$).

Attitudes towards the further use of modern ICT in solid organ transplant medicine

Overall, respondents were predominantly positive about the use of digital technologies in personal healthcare. 79.4% ($n=100$) expected positive effects on the doctor-patient relationship, and 81.7% ($n=103$) on the quality of treatment.

The usefulness of specific applications was assessed as follows: online appointment scheduling (92.2%, $n=119$), hospital apps (86.0%, $n=111$), digital transmission of medical findings (87.4%, $n=111$), messenger services in a medical context (77.0%, $n=97$), and video consultations (66.7%, $n=84$).

With further integration of modern ICT into personal healthcare, 89.8% ($n=115$) expected improved access to treatment teams, 82.8% ($n=106$) expected savings in travel costs, and 74.0% ($n=94$) expected time savings. Participants with lower levels of education were significantly more likely to see the greatest advantage in being able to undergo examinations at home, which was perceived as a safety factor due to the familiar environment ($p=0.032$). No consistent differences in expectations towards modern ICTs were observed between patients before and after transplantation, nor between patients in the early (<12 months) and late (≥ 12 months) post-transplant period.

The willingness to share personal medical information digitally with treating physicians was expressed by 65.1% ($n=84$). However, only 47.3% ($n=61$) of patients were willing to share personal medical data digitally with health insurance companies. A lower level of education was associated with a lower willingness to share personal health data digitally with both physicians ($p=0.01$) and health insurance companies ($p=0.013$).

With regard to data protection, only a minority expressed concerns about the use of email (20.3%, $n=26$), online appointment scheduling (9.4%, $n=12$), video consultations (22.7%, $n=29$), or hospital apps (17.3%, $n=22$). Messenger services, on the other hand, were viewed more critically (45.3%, $n=58$). Women were significantly more likely than men to have concerns about video consultations ($p=0.019$).

Attitudes toward the use of AI in solid organ transplantation medicine

The study participants' experience with AI tools such as ChatGPT was limited at the time of the survey (26.9%, $n=35$). Nevertheless, the majority considered AI to be a potentially useful addition to conventional care. 59.8% ($n=76$) expected an improvement in the quality of treatment and 58.3% ($n=74$) expected the prevention of medical errors through the use of AI.

The greatest confidence was placed in AI's ability to provide comprehensive information to support treatment (68.5%, $n=85$). Only 13.7% ($n=17$) believed AI could play a role in emotional care.

Diagnostic competence, therapy planning, and emotional support in particular were attributed significantly more to human professionals ($p<0.001$). Accordingly, 95.3% ($n=122$) preferred personal care by medical

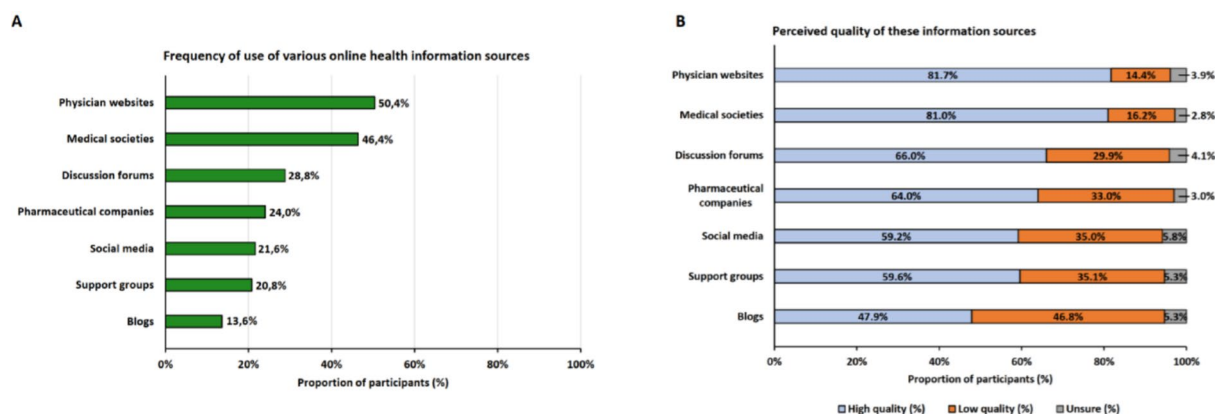


Fig. 2. Online health information seeking and perceptions of information quality among kidney transplant patients: (A) Proportion of participants using different online health information sources (multiple responses possible). (B) Participants' ratings of the perceived quality of these information sources, categorized as high quality, low quality, or unsure.

professionals – even if AI would theoretically enable more objective analyses. In addition, 89.8% ($n = 114$) were in favor of doctors retaining overall responsibility, even when AI is used. Subgroup analyses showed:

- Age: Younger participants were significantly more open to AI, while older participants placed greater responsibility on human professionals (96.8% vs. 82.8%, $p = 0.034$).
- Level of education: Higher education was associated with greater trust in AI diagnosis (60.7% vs. 37.3%, $p = 0.022$), treatment planning (71.4% vs. 50.7%, $p = 0.028$), medical history evaluation (69.1% vs. 42.6%, $p = 0.004$), improvement in quality of care (73.2% vs. 49.3%, $p = 0.014$), and error prevention (75.0% vs. 45.1%, $p = 0.003$) (Fig. 3).
- Gender: Men had greater trust in AI-generated treatment suggestions (64.6% vs. 42.3%, $p = 0.020$) (Fig. 3).
- eHealth literacy: Higher literacy was associated with greater trust in AI for error reduction (72.2% vs. 52.7%, $p = 0.033$) and treatment planning (65.7% vs. 45.3%, $p = 0.042$) (Fig. 3).
- The use of chatbots such as ChatGPT was significantly more common among younger (36.4% vs. 17.2%, $p = 0.014$), more highly educated (48.3% vs. 9.7%, $p < 0.001$), and more eHealth-competent participants (39.5% vs. 21.7%, $p = 0.038$).
- No consistent differences in attitudes toward artificial intelligence were observed between patients before and after transplantation, nor between patients in the early (< 12 months) and late (≥ 12 months) post-transplant period.
- In a multivariable analysis, none of the EQ-5D dimensions showed a significant independent association with the digital health or AI-related outcomes presented in Table 2.

Further group-specific results are shown in Table 2; Fig. 3.

Discussion

Our study shows that kidney transplant recipients are generally open to remote healthcare solutions. Our findings are consistent with previous studies that documented a positive attitude towards information and communication technologies (ICT) among this patient group^{24,25}. At the same time, it was also made clear that the use of artificial intelligence (AI) in transplant medicine is considered useful, provided that medical responsibility remains paramount. The main determinants of limited openness were older age, lower educational level, low eHealth literacy, and female gender. This suggests that the implementation of digital solutions should be more tailored to the needs of specific subgroups.

Use of modern ICT

The prevalence of computers and smartphones in our cohort was comparable with that of the general population.^{26,27} This finding is consistent with results from previous studies on chronic diseases, which documented widespread use of digital devices.^{20,28} However, although the prevalence of wearables in this patient

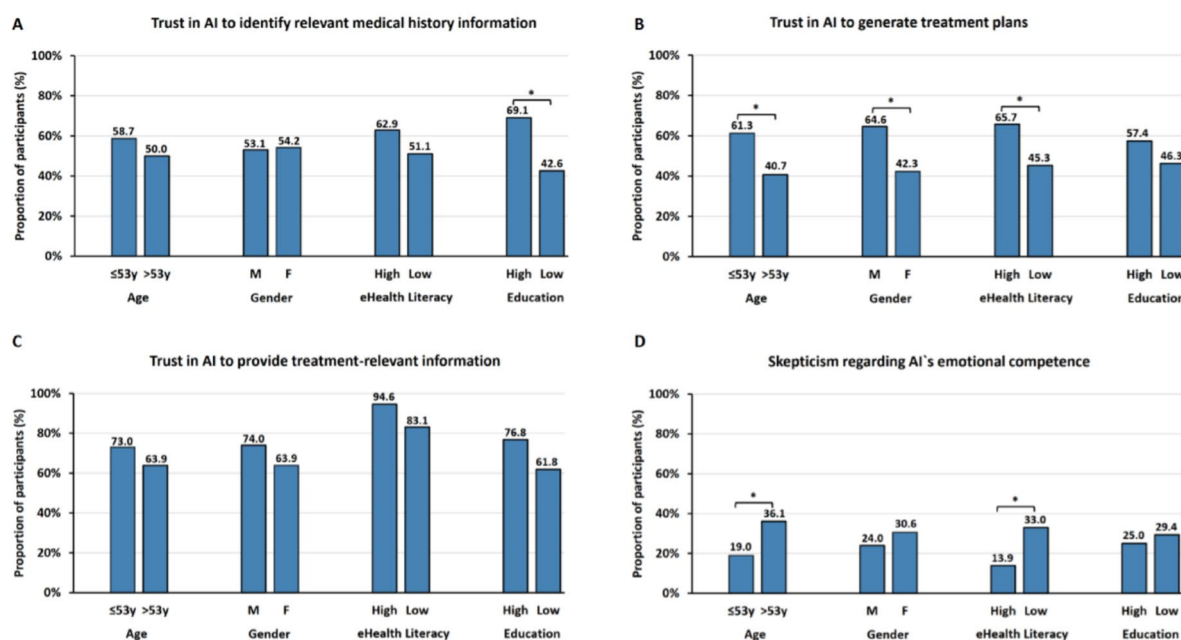


Fig. 3. Attitudes of kidney transplant patients towards the use of artificial intelligence (AI) in transplant medicine according to age, gender, eHealth literacy, and education level. The figure shows the proportion of participants who agreed with the respective survey statement. Differences between subgroups were analyzed using the chi-square test. * P -value ≤ 0.05 .

Variable	Approval of Outpatient Treatment Supported by Online Communication	Willingness to Share Health Data with the Physician via Clinic App	Comprehension of the Concept of AI	Belief in the Ability of AI to Create Appropriate Treatment Plans	Concerns About AI's Empathic Skills	Confidence in ChatGPT's Ability in Addressing Health-Related Questions
	Adjusted OR [95%-CI]	Adjusted OR [95%-CI]	Adjusted OR [95%-CI]	Adjusted OR [95%-CI]	Adjusted OR [95%-CI]	Adjusted OR [95%-CI]
Age						
per 10-year increase	1.38 [0.98–1.95]	0.82 [0.61–1.10]	1.01 [0.75–1.36]	0.78 [0.59–1.05]	1.34 [1.01–1.79]	1.06 [0.75–1.47]
Gender (ref. Female)						
Male	0.99 [0.36–2.74]	1.34 [0.59–3.06]	1.01 [0.44–2.31]	2.55 [1.14–5.69]	0.52 [0.24–1.14]	2.03 [0.79–5.26]
ISCED Level (ref. Low/Medium)						
High	2.90 [0.96–8.75]	3.73 [1.57–8.89]	5.35 [2.23–12.79]	1.72 [0.77–3.83]	0.90 [0.41–1.96]	2.37 [0.91–6.15]
eHealth Literacy Score						
per 1-point increase	1.11 [1.02–1.21]	1.06 [0.99–1.13]	1.11 [1.03–1.20]	1.04 [0.97–1.12]	0.98 [0.92–1.04]	1.11 [1.02–1.21]

Table 2. Multiple logistic regression of attitudes towards ICT and AI in relation to age, gender, ISCED level, and eHealth literacy. Grey fields are statistically significant with a P-value ≤ 0.05. Ref.: reference level; OR: odds ratio; CI: confidence interval; ISCED: International Standard Classification of Education.

population has increased in recent years, their use remains limited.²⁰ Compared with the study by Holderried et al.²⁰, which was conducted prior to the COVID-19 pandemic, participants in the present study expressed more positive expectations regarding the impact of digital technologies on the quality of care and doctor-patient communication. This finding could point to a broader trend towards greater acceptance and normalisation of digital health technologies in the post-pandemic era. At the same time, the comparison should be interpreted with due caution, as differences in the study populations, recruitment procedures and sample characteristics may also have contributed to the observed results.

Against the backdrop of the increasing relevance of wearables in everyday clinical practice, this reveals a previously untapped and therefore expandable potential for transplant medicine - both in terms of improving the quality of and the efficiency of care.⁷ It is also interesting to note that men used wearables more frequently than women. This difference could reflect gender-specific patterns in the use of technology, as has also been described in other health-related contexts.²⁹ Further research would also be useful to clarify whether cultural factors, perceptions of usefulness, or different preferences regarding self-monitoring are responsible for this difference³⁰.

The use of the internet was almost universal, only a very small minority of patients (3.9%) did not use it at all. This differs significantly from findings in patients with chronic kidney disease, among whom around one-fifth reported not using the internet.³¹ Transplant recipients therefore appear to be comparatively tech-savvy and could therefore benefit particularly from digital services. Nevertheless, our results point to a clear “digital divide”: older and less educated participants used digital applications significantly less often. This finding has direct consequences for clinical practice, as there is a risk that the very patient groups already considered vulnerable may be further disadvantaged by digital innovations.

Mobile applications and eHealth literacy

Mobile applications are being discussed as promising tools for transplant care. Their potential in telemonitoring and patient-centered education has been proven in other studies.¹⁷ Beyond the monitoring of general health parameters, digital health applications may be particularly valuable for supporting adherence to immunosuppressive medication, which is a critical determinant of long-term graft outcomes.^{32,33} However, our study shows that the actual use of mobile health apps in this patient group has been very low so far. One plausible explanation for this is the limited availability of high-quality, German-language applications that can be prescribed.³⁴ While English-language apps are becoming increasingly available, the range of apps in German-speaking countries remains very limited.³⁵ This shortage represents a significant barrier that should be addressed through targeted promotion and quality testing of digital health applications.

Another key factor for the use of digital health technologies is eHealth literacy. The average score in our cohort was comparable to that of the general population, yet around two-thirds achieved only moderate or low scores.^{36,37} This indicates a significant gap in digital health literacy. Older and less educated patients showed less trust in online information and used digital channels less frequently. In practice, this means that patient-oriented education and training programs are necessary to specifically strengthen digital health literacy. Such measures could make a decisive contribution to making access to digital solutions more equitable.

Data privacy and acceptance

Data privacy concerns are a key issue in the digital transformation of healthcare. In our cohort, the majority expressed only minor concerns, suggesting that the transplant population appears to be more open in this regard than patients from other medical contexts.³⁸ However, women and less educated participants expressed concerns significantly more often. This suggests that data security and transparency need to be specifically addressed in order to gain the trust of these subgroups. Clear communication about encryption standards, server locations, and terms of use could play a key role in this context. Our findings also show that attitudes toward ICT have changed significantly since the coronavirus pandemic.²⁰ While less than half of respondents expected positive

effects on treatment quality at that time, this figure now stands at 81.7%. Expectations of improved doctor-patient communication also increased markedly. These differences should be interpreted with caution, as they may not only reflect temporal changes but could also be influenced by differences in patient populations and sampling between the two studies, despite both studies investigating kidney transplant recipients. Nevertheless, the observed trend may be related to the pandemic-driven establishment of digital services and the increasing normalization of digital technologies in society.^{39,40} It is noteworthy, however, that many participants reported no change in their personal views as a result of the pandemic. This suggests that the observed increase is driven less by short-term effects and more by the broader momentum of digitalization in healthcare.

At the same time, data sharing remains a sensitive issue. Less educated patients in particular expressed reservations about sharing their health information digitally. Thus it will be crucial to develop measures to overcome this barrier. These could include easily accessible applications, low-threshold training programs, and clear governance structures for data use. Furthermore, patients were less willing to share their medical data with insurance companies than with their treating physician. This may reflect concerns regarding data privacy, potential secondary use of health data, or possible socioeconomic consequences. Addressing these concerns through transparent data governance and clear communication will be essential for the successful implementation of digital health technologies.

Use of AI in transplant medicine

Our work is among the first studies to analyze the attitudes of kidney transplant patients towards AI. The majority of respondents see AI as a supportive tool for improving the quality of care and reducing medical errors. At the same time, there was skepticism about the social and communicative abilities of AI, especially in terms of emotional support. This differentiation shows that patients are willing to accept AI as a technical aid, but consider the human factor to be indispensable. Comparable results have been reported in studies of the general population, in which medical advice was considered less trustworthy once AI involvement was disclosed.^{41–43} Our findings suggest that the successful implementation of AI in the care of kidney transplant patients should follow a blended-care approach, in which AI supports but does not replace clinical decision-making. Potential applications include the individualized optimization of immunosuppressive dosing, risk stratification, and the prediction of graft dysfunction or rejection using machine learning models and digital pathology^{16,44}. At the same time, overall responsibility for diagnosis, treatment decisions, and communication with patients should remain with the treating physicians. This approach directly addresses the clear preference for human oversight observed in our study and can help reconcile the perceived benefits of AI with patients' concerns regarding its medical and empathetic capabilities.

Our present subgroup analyses showed that younger, better educated, and more eHealth-competent participants were significantly more open to AI, while older and female patients expressed greater reservations. These findings highlight the need for targeted information and education strategies, as described in recent studies in other medical fields.^{28,45} Experience from the general population suggests that early involvement of patients in implementation and transparent presentation of possible applications can promote acceptance.⁴⁶ For solid organ transplant medicine, this means that new technologies should not be introduced in isolation, but developed in close dialogue with those affected.

Implications and outlook

Our results indicated that despite the widespread availability of digital devices, the majority of patients still relied on analogue processes, such as paper-based documentation of clinical parameters. However, continued reliance on paper-based documentation may contribute to fragmented information flow, delayed availability of patient-generated health data, and increased risk of transcription errors.⁴⁷ Structured patient education and training programs may facilitate the adoption of digital technologies and support the transition from analogue processes to validated digital solutions, including patient portals, mobile applications for health data documentation, and remote communication tools.¹⁹ In particular, transplant-specific digital applications could support medication intake, laboratory monitoring, and communication with the transplant team.⁴⁸ This may help identify adherence problems earlier and provide targeted counselling when needed. Although medication adherence and tacrolimus trough levels were not examined in the present study, future research should investigate the impact of digital health technologies on these clinically important outcomes. Additional relevant outcomes for future studies could include allograft function, rejection episodes, and hospitalizations, which may be also associated with the use of digital health technologies.

Translating the potential benefits of digital health technologies into routine transplant care requires not only effective applications but also appropriate regulatory and reimbursement pathways. In Germany, the DiGA framework enables the prescription and reimbursement of evidence-based digital applications. However, a widely available, transplant-specific DiGA is still lacking, possibly due to the small and heterogeneous target group, high requirements for evidence and data security, and the complex integration into clinical processes and hospital information systems. Our findings can support the future development of transplant-specific digital applications by highlighting relevant requirements and preferences, as well as differences in digital readiness, trust, data sharing, and digital health literacy. Regulatory frameworks such as the EU AI Act or the Medical Device Regulation (MDR) will have a significant impact on the use of digital technologies. In practice, it is therefore essential to consider data protection, interoperability, and quality standards at an early stage.

Against this background, our findings regarding patients' willingness to share personal medical data deserve particular attention. Participants expressed a lower willingness to share personal medical data with health insurance companies than with treating physicians. This could reflect greater trust in the immediate therapeutic relationship, but it may also stem from concerns about secondary data use, a loss of control over sensitive health information, or potential socioeconomic consequences. Since these reasons were not directly assessed in the

present study, they should be interpreted merely as possible explanations and explicitly investigated in future studies.

A promising approach to further promote the adoption of digital health technologies could involve co-design processes, in which patients, physicians, and developers design applications together.⁴⁹ Such participatory approaches can help ensure that applications take into account the needs of those affected, address relevant barriers, and can be realistically integrated into clinical workflows. Longitudinal studies are needed to examine how attitudes, acceptance, and usage patterns change over time and following implementation into routine care. Future evaluations should also examine the impact of digital technologies on clinical quality, patient safety, and risk management, while systematically considering socioeconomic and health economic aspects such as equitable access, resource allocation, and cost-effectiveness.

Overall, our findings clearly show that digital solutions have great potential in solid organ transplant care, but at the same time, issues of equal opportunity and equitable access must be addressed. Otherwise, there is a risk of exacerbating existing health inequalities.

Limitations

The study has several limitations. First, the results are based on self-reported data, which may limit accuracy and could be subject to response biases, including social desirability bias and self-assessment bias. Furthermore, a non-response bias could not be excluded due to the lack of demographic and clinical data for non-responders. Second, although selected multi-item domains demonstrated acceptable to high internal consistency in a Cronbach's alpha analysis, the study-specific questionnaire was designed as an exploratory measurement tool and was not subjected to a formal pilot study or a psychometrically validation. Thus, construct validity was not formally assessed, which may limit the comparability of some study-specific items. Third, although dichotomizing the Likert scales and continuous variables improved the clarity and interpretability of the results, it may have reduced the statistical power and obscured more nuanced associations.

Fourth, the study was conducted at a single tertiary university transplant center in Germany, and both center-specific and healthcare system-specific factors may have influenced the findings. For example, the majority of participants in our study were female, whereas kidney transplant recipients are predominantly male worldwide.⁵⁰ This imbalance may have influenced some of the results, as gender-specific differences were observed in several aspects of digital technology use, privacy concerns, and trust in AI-based therapy recommendations. Furthermore, the relatively high level of education among our study population, the comparatively high proportion of living donor kidney transplant recipients and the clinical heterogeneity of the cohort, which included patients both before and after kidney transplantation, as well as transplant recipients at different stages of follow-up, may have affected attitudes towards digital health technologies and AI. Although exploratory subgroup analyses did not reveal consistent differences between pre- and post-transplant patients or between early and late post-transplant phases, the available clinical data did not allow for a more differentiated classification based on graft function or clinical stability. In addition, household income was not assessed, precluding a more comprehensive evaluation of socioeconomic determinants of digital readiness and AI acceptance. Moreover, characteristics of the German healthcare system, including the limited integration of patient-generated health data into hospital information systems and the incomplete availability of standardized interoperable interfaces may have contributed to the continued reliance on paper-based documentation. These factors may restrict the generalizability of the findings to other transplant centers and healthcare systems.

Finally, the cross-sectional study design of our study precludes causal inference and does not permit conclusions regarding temporal relationships between patient characteristics and attitudes. Consequently, changes in attitudes towards digital health technologies and AI over time could not be evaluated.

Conclusion

Kidney transplant patients are predominantly open to remote healthcare technologies and AI, but primarily view them as a supplement to medical care. Age, educational level, eHealth literacy, and gender proved to be key factors in acceptance. This makes it clear that standardized “one-size-fits-all” solutions do not meet the needs of this patient group. Tailored strategies and target group-specific digital health applications are required, encompassing patient-centered education, skills development, and clear integration into existing care pathways. If these conditions are met, remote healthcare technologies and AI can make a decisive contribution to making transplant medicine fit for the future.

Data availability

The datasets of the current study are available from the corresponding author on reasonable request.

Received: 5 October 2025; Accepted: 16 September 2026

Published online: 24 September 2026

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Acknowledgements

We wish to thank Susanne Geiger and Katharina Möck for supporting our study.

Author contributions

FE, LS, AP, MG, MH, and FH were engaged in the study conception and design. FE and MG were responsible for patient recruitment. FE, MG, and MH performed data collection and analysis. FE wrote the first draft of the manuscript, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-026-72468-0>.

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