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ТОШКЕНТ-2025

МИНИСТЕРСТВО ЗДРАВООХРАНЕНИЯ РЕСПУБЛИКИ УЗБЕКИСТАН ОБЩЕСТВЕННОЕ ОБЪЕДИНЕНИЕ НЕВРОЛОГОВ УЗБЕКИСТАНА

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ANNOTATSIYA

So‘nggi yillarda “Bosh Bosh miya-kompyuter interfeysi” texnologiyalari sohasidagi yutuqlar nevrologik funksiyalarni tiklash va reabilitatsiya qilishda yangi davrni boshlab berdi. Ushbu texnologiyalar nogironlik keltirib chiqaruvchi nevrologik kasalliklarga chalingan insonlarga, xususan kranioserebral travmalarning oqibatlarida atrof-muhit bilan o‘zaro muloqot qilish, kundalik hayotdagi muhim vazifalarni bajarish hamda shaxsiy maqsadlariga erishish imkoniyatini berishga yo‘naltirilgan.

Mazkur maqolada “Bosh miya-kompyuter interfeysi” (BMKI) texnologiyalarining asosiy tamoyillari, afzalliklari, muammolari va kelajakdagi rivojlanish istiqbollari neyroreabilitatsiya nuqtai-nazaridan tahlil qilinadi. Shuningdek, ushbu texnologiyalarning klinik amaliyotdagi qo‘llanilishi ko‘rib chiqilib, nevrologik kasalliklarga chalingan bemorlarda, jumladan kranioserebral travmalar oqibatlarida BMKI tizimlarini joriy etish bo‘yicha yondashuvlar taklif etiladi.

Kalit so‘zlar: bosh miya–kompyuter interfeysi; neyroreabilitatsiya; neyrotexnologiyalar; kranioserebral travmalar oqibatlari.

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ЗНАЧЕНИЕ «МОЗГ-КОМПЬЮТЕР» ИНТЕРФЕЙСОВ В НЕЙРОРЕАБИЛИТАЦИИ ПОСЛЕДСТВИЙ КРАНИОЦЕРЕБРАЛЬНОЙ ТРАВМЫ (ОБЗОР ЛИТЕРАТУРЫ)

АННОТАЦИЯ

В последние годы достижения в области технологий «интерфейса мозг-компьютер» открыли новую эру в восстановлении и реабилитации неврологических функций. Эти технологии направлены на то, чтобы дать возможность людям с инвалидизирующими неврологическими заболеваниями, в частности, пострадавшим от краниоцеребральной травмы, взаимодействовать с окружающей средой, выполнять важные задачи в повседневной жизни и достигать личных целей.

В данной статье анализируются основные принципы, преимущества, проблемы и перспективы развития технологий «интерфейса мозг-компьютер» (ИМК) с точки зрения нейрореабилитации. Также рассматривается применение этих технологий в клинической практике и предлагаются подходы к внедрению систем ИМК у пациентов с неврологическими заболеваниями, в том числе с разлиными последствиями краниоцеребральной травмой.

Ключевые слова: мозг-компьютер интерфейс; нейрореабилитация; нейротехнологии; последствия краниоцеребральной травмы.

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THE IMPORTANCE OF «BRAIN-COMPUTER» INTERFACES IN NEUROREHABILITATION FOR OUTCOMES OF TRAUMATIC BRAIN INJURIES (LITERATURE REVIEW)

ABSTRACT

In recent years, advances in brain-computer interface technologies have ushered in a new era in the restoration and rehabilitation of neurological functions. These technologies aim to enable individuals with disabling neurological conditions, particularly those outcomes of traumatic brain injuries (TBI), to interact with their environment, perform important tasks of daily living, and achieve personal goals.

This article analyzes the basic principles, advantages, challenges, and prospects for the development of brain-computer interface (BCI) technologies from a neurorehabilitation perspective. It also examines the application of these technologies in clinical practice and proposes approaches to implementing BCI systems in patients with neurological conditions, including those with various sequelae of TBI.

Keywords: brain-computer interface; neurorehabilitation; neurotechnology; outcomes of TBI.

Kirish: So‘nggi 20 yil ichida kompyuter texnologiyalari, biomuhandislik va neyrojarrohlik kabi fanlarning parallel rivojlanishi “Bosh miya-kompyuter interfeysi” (BMKI) orqali neyroreabilitatsiyani qo‘llab-quvvatlashda misli ko‘rilmagan natijalarga olib keldi. Tez sur’atlarda rivojlanayotgan BMKI texnologiyalari sohasi hamda uning klinik tadqiqotlar va amaliyotga ta’siri nevrologik kasalliklar yoki neyrojarrohlik natijasida, xususan kranioserebral travmalar oqibatlarida yuzaga kelgan barqaror funksional buzilishlarga ega bemorlarga optimal yordam ko‘rsatishga intilayotgan shifokorlar uchun tobora dolzarb ahamiyat kasb etmoqda [1, 2].

Yo‘qotilgan funksiyalarni tiklash yoki ularning o‘rnini bosish imkonini beruvchi BMKI texnologiyalari bemorlarning hayot sifatini sezilarli darajada yaxshilaydi, ijtimoiy izolyatsiyani kamaytiradi va jamiyatga qayta integratsiyalashuviga yordam beradi [3, 4].

Mazkur maqolada BMKI texnologiyalarining tamoyillari, afzalliklari, muammolari va imkoniyatlari neyrofunksional tiklanish nuqtai-nazaridan tahlil qilinadi. Shuningdek, bu texnologiyalarni kranioserebral travmalar oqibatlarida va boshqa turdagi nevrologik yetishmovchiliklarda klinik amaliyotda qo‘llash hamda turli bosqichdagi nevrologik kasalliklarda ulardan foydalanish uchun amaliy yondashuv taklif etiladi. “Miya tiklanishi” (neyrocovery) atamasi to‘g‘ridan-to‘g‘ri texnologiya (masalan, BMKI) yordamida qayta tiklangan funksiyani anglatadi. “Neyroreabilitatsiya” esa asosan saqlanib qolgan yoki shikastlanmagan asab tizimi tomonidan yo‘qotilgan funksiyani qayta o‘rganish yoki tiklash jarayonini bildiradi. Shu sababli “neyrocovery” atamasi kengroq tushuncha bo‘lib, u maqsadni ifodalaydi, lekin unga turli yondashuvlar orqali erishish mumkin.

Bosh miya–kompyuter interfeysi nima?

Bosh miya–kompyuter interfeysi (BMKI) – bu markaziy asab tizimidan (MAT) kelayotgan signallarni tashqi yoki ichki qurilmaga boshqaruv buyrug‘i shaklida o‘zgartirib beruvchi tizimdir.

Ushbu texnologiyaning tarixiy asosi XIX asrda Richard Keyton, Adolf Bek va Xans Berger kabi olimlarning kashfiyotlariga borib taqaladi. Ular miyada uzluksiz elektr faolligi mavjudligini aniqlab, nerv tizimi impulslarini o‘lchash va tahlil qilish uchun ilmiy asos yaratdilar [5, 6]. Mazkur kashfiyotlar primatlar ustida olib borilgan muhim tadqiqotlar, shuningdek elektroensefalografiya (EEG) asosidagi neyrobioboshqaruv tizimlari va dastlabki BMKI prototiplarini ishlab chiqishga zamin yaratdi [7–12]. Bugungi kunda “BMKI” atamasi nerv tizimi bilan o‘zaro ta’sirlashuvchi keng doiradagi texnologiyalarni o‘z ichiga oladi – masalan, eshitish qobiliyatini tiklash uchun mo‘ljallangan koxlear implantlar yoki farmakorezistent epilepsiyani davolashda qo‘llaniladigan NeuroPace qurilmasi [13,14].

Umuman olganda, BMKI texnologiyalarining maqsadi – insonning yo‘qotilgan funksiyalarini tiklash yoki ularni reabilitatsiya qilish orqali bemorning atrof-muhit bilan muloqotini, harakat faoliyatini va o‘zini ifoda etish imkoniyatlarini kengaytirishdir [15]. Yo‘qotilgan funksiyani tiklash, odatda, kasallik yoki shikastlanish natijasida zararlangan nerv yo‘llarini chetlab o‘tish va ularning o‘rnini bevosita BMKI orqali to‘ldirishni anglatadi. Masalan: BMKI yordamida protez qo‘lni boshqarish – yo‘qolgan qo‘l funksiyasini bajarish imkonini beradi [16–22]. Yoki nutq funksiyasini yo‘qotgan bemorlarda BMKI orqali yozma, yoki og‘zaki muloqotni ta’minlash [23–31] imkoniyati mavjud. Bunday texnologiyalar shikastlangan miya sohalarini aylanib o‘tib, odatda shu funksiyani bajaruvchi sohalarning faoliyatini o‘rnini bosuvchi yangi nerv yo‘llari ish faoliyatini yaratadi.

BMKI yordamida nerv funksiyasini reabilitatsiya qilish.

BMKI yordamida nerv funksiysiani reabilitatsiya qilish jarayoni odatda neyrobioregulyatsiya (biofeedback) va neyrostimulyatsiya texnologiyalarini o‘z ichiga oladi. Bu yondashuvlar miya plastiklik darajasini oshirish va yo‘qotilgan funksiyalarni qayta o‘rganishga imkon yaratish maqsadida qo‘llanadi [32]. Bunda shikastlanishni aylanib o‘tish emas, balki asab tizimining tabiiy tiklanish salohiyatini faollashtirish maqsad qilinadi [33].

Masalan, BMKI asosidagi tayanch-harakat tizimida insultdan so‘ng gemiparezga uchragan bemorlar qo‘l-oyoq funksiyasini asta-sekin tabiiy holatga qaytarish [34-36] ni keltirish mumkin. Bunday reabilitatsion BMKI yondashuvlar kortikal, subkortikal yoki orqa miya plastiklik mexanizmlarini faollashtirish orqali neyronlarning qayta tiklanishi va neyron tarmoqlarining qayta shakllanishini rag‘batlantiradi [37].

BMKI larning yana bir ahamiyati – bu ong buzilishlarida diagnostik aniqlikni oshirish bo‘lib, bu orqali neyroreabilitatsiya imkoniyatlarini kengaytiradi. Kutilganidek, BMKI tizimlari yashirin reaktivlikni (ya’ni bemorni nevrologik tekshiruvda aniqlab bo‘lmaydigan, lekin mavjud bo‘lishi mumkin bo‘lgan patologiyalarni) baholashga yordam berishi mumkin. Ong buzilishlariga ega bunday bemorlarga xulq-atvorni an’anaviy baholash usullari yordamida ko‘pincha noto‘g‘ri tashxis qo‘yiladi, chunki bu usullar harakat tizimlari butun bo‘lishiga yoki yuqori darajadagi kognitiv (aql-idrok) qobiliyatlar mavjudligiga juda ko‘p darajada tayanadi [38–41]. Masalan, bir turdagi BMKI tizimi ko‘rish fiksatsiyasini (nigohni muayyan nuqtada ushlab turishni) baholash uchun ishlatilgan. Ko‘rish fiksatsiyasini tekshirish bo‘yicha kompyuter interfeysi EEG bilan birlashtirilib, ushbu tizim orqali bemorning ong holatini aniqlashga yordam berishni maqsad qiladi. Bu yondashuv, ba’zan bemorda o‘tkaziladigan xulq-atvorni an’anaviy baholash usullari yordamida aniqlanmay qoladigan ong buzilish belgilarini aniqlash imkonini beradi [42-43].

“Bosh miya-kompyuter interfeysi” komponentlari: kognitiv funksiyalarni faollashtirish.

BMKI ning asosiy komponentlari quyidagi uchlikdan iborat: datchik (sensor), dekoder va effektor [47]. BMKI datchigi neyron ma’lumotlarni aniqlash va yozib olish uchun xizmat qiladi, dekoder esa bu ma’lumotlarni qayta ishlaydi va ularni buyruq signaliga aylantiradi, so‘ngra bu signal effektorga uzatiladi, u esa tegishli funksiyani bajaradi. Muhim jihati shundaki, foydalanuvchiga sensor qayta aloqa taqdim etiladi – bu odatda ko‘rish orqali (vizual shaklda) amalga oshiriladi [48-49].

Shuningdek, eshitish [50] va taktil qayta aloqa [51-52] asosidagi yondashuvlarda ham bosh miya-kompyuter interfeysi (BMKI) neyroreabilitatsiya sohalarida qo‘llanilmoqda. BMKI datchiklari asosan markaziy asab tizimining elektr, gemodinamik yoki magnit signallarini qayd etadi.

Elektr signallarni qayd etishga mo‘ljallangan datchiklar quyidagi usullardan foydalanadi:

– Elektroensefalografiya (EEG) – bosh terisi yuzasidan elektr faolligini o‘lchash,

– Elektrokortikografiya (ECoG) – miya yuzasidan to‘g‘ridan-to‘g‘ri elektr signalini yozib olish,

– Ichki kortikal mikroelektrodlar – miya to‘qimalarining ichki qatlamlaridan signal olish.

Gemodinamik signallarni qayd etuvchi datchiklar esa quyidagi usullardan foydalanadi:

– Funktsional magnit-rezonans tomografiya (FMRT),

– Yaqin infraqizil sohada funktsional spektroskopiya (FNIRS).

Bu usullar qonning kislorodga to'yinishi darajasidagi oʻzgarishlarga asoslanadi va shu orqali faollashgan neyron sohalarni aniqlash imkonini beradi [53, 54]. Magnitoensefalografiya (MEG) – bu sinxron neyron oqimlari tomonidan hosil qilinadigan miyaning magnit signallarini qayd etish uchun ishlatiladigan asosiy usuldir [55]. Koʻp rejimli (multimodal) datchiklar esa turli xil signallarni birlashtirib qayd etish orqali oʻlchashning samaradorligini oshirishi mumkin. Bunday multimodal datchiklarga misol sifatida MEG va EEG kombinatsiyasi [56] yoki EEG va fMRT kombinatsiyasi [57] keltiriladi.

Datchiklar oʻz joylashuvi boʻyicha farqlanadi, masalan:

– miya chuqur tuzilmalariga implantatsiya qilingan,
– bosh miya po'stlog'iga joylashtirilgan,
– subdural (bosh miya qattiq pardasi ostida),
– epidural (bosh miya qattiq pardasi ustida),
– intra- yoki epikranial,
– bosh terisiga oʻrnatilgan,
– boshning tashqarisiga joylashtirilgan turlari mavjud.

Shuningdek, ular quyidagi jihatlariga koʻra ham farq qiladi:

– vaqtinchalik aniqligi (ya'ni signalni qayd etish tezligi),
– fazoviy aniqligi (ya'ni aniqlashning batafsilligi),
– signal/shovqin nisbati,
– datchik hajmi,
– va uzoq muddat davomida signal yozib olish qobiliyati [58].

Elektr signallarni qayd etuvchi datchiklar – xususan EEG va MEG – nevrologik kasalliklarga chalingan odamlarda harakat faoliyatini va muloqot imkoniyatlarini tiklash uchun ishlatiladigan eng keng tarqalgan BMKI datchiklari hisoblanadi.

Neyron dekodlash: neyron ma'lumotni tarjima qilish.

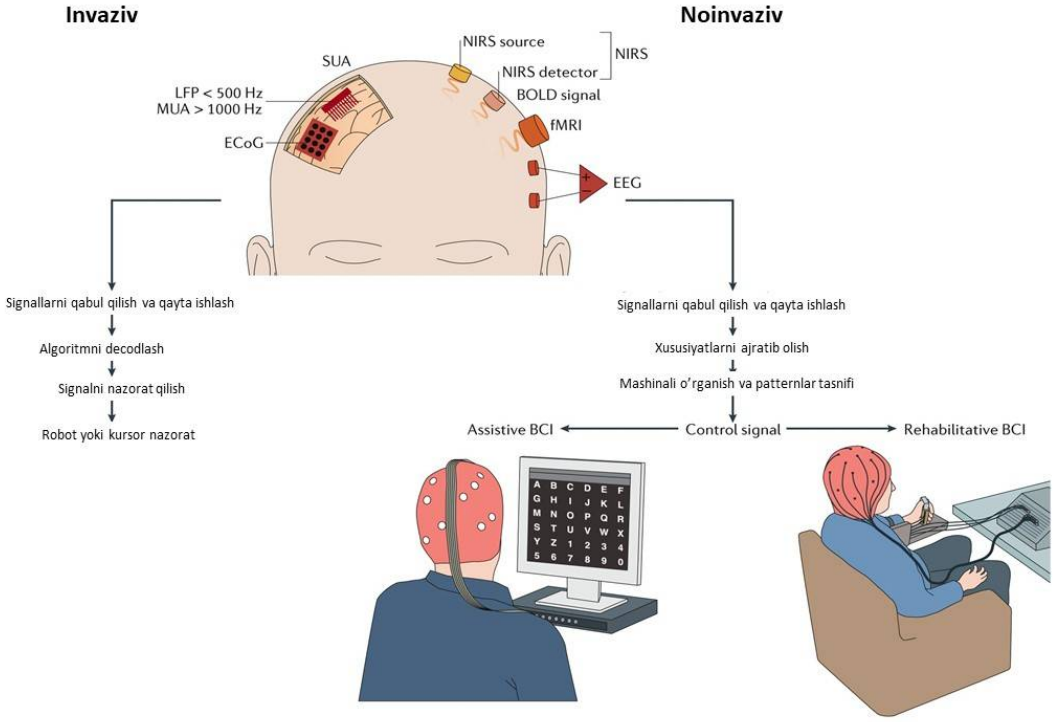
Neyron faolligi yoki uning vositachisi datchik tomonidan qayd etilib yozib olingandan soʻng, IMK dekoderi bu ma'lumotni algoritm yordamida qayta ishlaydi va foydali chiqish signalini faollashtirish uchun effektorga uzatiladigan buyruq signalini shakllantiradi.

Neyron dekodlash algoritmlari neyron faollikdagi shakllarni foydalanuvchining kutilgan hatti-harakati yoki niyati bilan bogʻlaydi [47, 59]. Dastlab, neyron dekodlash algoritmlari chiziqli statistik tahlil usullariga asoslangan edi – masalan, Kalman filtri (yoki chiziqli-kvadratik baholash deb ham ataladi). Biroq, hisoblash quvvatining ortishi va sun'iy intellekt texnologiyalarining rivojlanishi natijasida, mashina oʻrganish (machine learning) usullari yordamida BMKI tizimlarining samaradorligi ancha oshmoqda [60–61].

Neyron dekodlash sohasidagi ushbu yutuqlar, foydalanuvchining kutilgan harakatlarini aniqlashdagi ayrim BMKI tizimlarining barqarorligini cheklab kelgan neyron faollikdagi oʻzgaruvchanlikni hisobga olish orqali, BMKI samaradorligini yanada oshirish istiqbollarini ochib bermoqda [29].

Neyron effektor va qayta aloqa: xohishni harakatga aylantirish.

BMKI effektorlari – bu neyron dekoder tomonidan olingan signallarni qayta ishlovchi va kerakli natijani hosil qiluvchi qurilmalardir. BMKI effektorlari misollariga quyidagilar kiradi: Kompyuter kursori [62], Robotlashtirilgan ortozlar [63-67], Ekzoskeletlar [68-70], Nogironlar aravachalari [71-73], Virtual reallik muhitlari (ya'ni foydalanuvchiga interaktiv mashq qilish imkonini beruvchi kompyuter simulyatsiyalari) [74-76], Sun'iy ovoz tizimlari [77, 78], Soʻzlarni bir zumda oʻqiydigan qurilmalar [79-83] yoki insonning oʻz qoʻl-oyoqlarini qayta harakatga keltirish (reanimatsiya) tizimlari [84-88].



1-rasm. Bosh miya-kompyuter» interfeyslarining turlari va ishlash tamoyillari.

Neyrobioregulyatsiya (neurofeedback) — bu ham funksiya tiklanishi (yopiq konturli boshqaruv), ham funksiya reabilitatsiyasi uchun muhim tarkibiy qism hisoblanadi. Eng keng tarqalgan neyrobioboshqaruv strategiyasi – audiovizual (AV) qayta aloqadir [89]. Real vaqt rejimida taqdim etiladigan audiovizual qayta aloqa ishtirokchilarda maxsus mashgʻulotlar va tiklanish jarayonini ragʻbatlantirish vositasi sifatida oʻrganilgan [90]. Neyrobioboshqaruv strategiyalariga, shuningdek, neyromodulyatsiya usullari ham kiradi, masalan:

– adaptiv chuqur miya stimulyatsiyasi,
– invaziv boʻlmagan miya stimulyatsiyasi.

Bu usullar asab tizimi faoliyatini oʻzgartirish orqali harakat, kognitiv yoki emotsional holatni yaxshilashga qaratilgan [91].

Masalan, taktil (sezgi orqali) yoki xulq-atvorli qayta aloqa yordamida insult natijasida qoʻl-oyoq zaifligi rivojlangan bemorlar ipsilateral (zararlangan tomondagi) miya yarim sharidagi ritm faolligini oshirishni va ipsilateral sensomotor tarmoqlarni faollashtirishni oʻrganishlari mumkin [91-93].

BMKIning eng muhim tarkibiy qismi bu – qayta aloqa (feedback) boʻlib, u foydalanuvchi bilan qurilma orasidagi "yopiq doira"ni (closed loop) hosil qiladi. Bu qayta aloqa: faqat vizual boʻlishi mumkin – masalan, kompyuter ekranidagi ikki oʻlchovli kursorni boshqarish yoki robot qoʻlning koʻp oʻlchovli harakati, yoki vizual va sezgi (sensor) qayta aloqa boʻlishi mumkin – masalan, funksional elektro-stimulyatsiya (FES) orqali qoʻl va bilak harakati paytida hosil boʻladigan sezgi javoblari [94] (1-rasm).

Tadqiqotlar shuni koʻrsatadiki, bunday qayta aloqa BMKI boshqaruvida ishtirok etuvchi alohida neyronlar va kortikal tarmoqlarning sozlanishiga taʼsir qiladi – bu hodisa "yopiq neyron moslashuvi" (closed-loop neural adaptation) deb ataladi [95].

Shuningdek, BMKI neyrobioregulyatsiya (neurofeedback) BMKI boshqaruvida ishtirok etuvchi neyronlar va neyron guruhlarining xususiyatlarini oʻzgartirishi aniqlangan [96, 97]. Bu oʻzgarishlarning yopiq zanjirli BMKI boshqaruvidagi ahamiyati keyingi tadqiqotlarda oʻrganilmoqda [98].

Hozirda tizimlashgan nerv fani (systems neuroscience) darajasida neyrobioregulyatsiya paradigmalarini neyroreabilitatsiyani yaxshilash maqsadida oʻrganish ishlari olib borilmoqda [99].

Neyrotiklanish (neurorestoration) va neyroreabilitatsiyada BMKI.

Neyrotiklanish va neyroreabilitatsiya kontekstida BMKIning maqsadi – jarohat yoki kasallik natijasida yoʻqotilgan funksiyalarni tiklashga qaratilgan boʻladi. BMKI yordamida tiklanishi mumkin boʻlgan funksiyalar quyidagilarni oʻz ichiga oladi: muloqot qilish qobiliyati, harakat (motor) funksiyasi, vegetativ funksiyalar (ichak, siydik pufagi va jinsiy funksiyalar), eshitish (masalan, kohlear implantlar orqali), koʻrish (masalan, retinal protezlar orqali).

BMKI shuningdek, neyron zanjirlar plastiklik (moslashuvchanlik) jarayonini qoʻzgʻatish orqali shikastlanishdan keyin yoʻqolgan funksiyani tiklash uchun ham xizmat qilishi mumkin. Miyaning struktural qayta tashkil topish (reorganizatsiya) qobiliyati neyropsixolog Donald Xebb tomonidan oʻrganilib, tizimlashtirilgan. U shunday faraz qilgan edi: "A hujayraning aksoni B hujayrani qoʻzgʻatishga yetarlicha yaqin boʻlsa va u B hujayrani takroran yoki doimiy ravishda faollashtirishda ishtirok etsa, u holda har ikkala hujayrada ham oʻsish yoki metabolik oʻzgarish jarayoni sodir boʻladi, natijada A hujayraning B hujayrani faollashtiruvchi taʼsiri kuchayadi. Yaʼni, bir vaqtning oʻzida bir necha marta faol boʻlgan har qanday ikkita hujayra yoki hujayralar tizimi "assotsiatsiyalanish" moyilligiga ega boʻladi, shunday qilib, bittasining faolligi boshqasining faolligini osonlashtiradi" [100].

Bu gʻoya – yaʼni bir vaqtda faollashuvchi neyronlar oʻzaro mustahkam sinaptik bogʻlanishlar hosil qilishi mumkinligi – hozirda Xebb plastiklik tamoyili deb nomlanadi. Qisqacha qilib aytganda: "Birgalikda faollashuvchi neyronlar oʻzaro bogʻlanadi" [101]. Shu tamoyilga muvofiq, ayrim BMKI tizimlari zararlangan neyronlar tufayli buzilgan funksiyalarni tiklash maqsadida, neyronlarning muayyan faollik shakllarini (patternlarini) stimulyatsiya qilish orqali sinaptik bogʻlanishlarni mustahkamlashga yoʻnaltirilgan.

Neyron plastiklikni (moslashuvchanlikni) qoʻzgʻatish (induksiya qilish) yondashuvlari quyidagilarni oʻz ichiga oladi: Neyron yoʻlining takroriy stimulyatsiyasi, Neyron yoʻlining bir nechta nuqtalarini juft (bir vaqtda) stimulyatsiya qilish, yoki yopiq siklli (closed-loop) stimulyatsiya – bu usulda neyron yoʻlining bir nuqtasidagi ichki (endogen) faollik neyron yoʻlining boshqa nuqtasini faollashtirishni boshlash uchun signal sifatida ishlatiladi [102].

BMKI (Bosh miya-kompyuter interfeysi) klinik amaliyotda.

Shifokorlar qanday qilib BMKI (Bosh miya-kompyuter interfeysi) tizimini bemorga tavsiya qilishi mumkin?

Neyroreabilitatsiya va neyroxirurgiya sohasida BMKI tizimi klinik amaliyotga joriy etilishi uchun bir qator murakkab ishlab chiqish bosqichlari va nazorat nuqtalaridan oʻtish zarur [103, 104]. Tibbiy qurilmalarni ishlab chiqish xarajatlari boshlangʻich loyihalashdan tortib yakuniy bosqichgacha juda katta sarflarni talab etadi [105]. Dastlabki tadqiqot va dizayn bosqichlaridan boshlab, BMKI tizimi klinik sinovlardan oʻtishi kerak, bu sinovlar orqali uning xavfsizligi va kutilgan samaradorligi isbotlanadi. Shundan soʻng u tegishli tartibga soluvchi organlar (masalan, AQShda FDA) tomonidan ruxsat olishi, shuningdek ishlab chiqarish va bozorga chiqarish bosqichlarida muvaffaqiyat qozonishi lozim, shundagina u amaliy klinik qoʻllanishga erishadi.

Bu murakkab jarayon nafaqat tadqiqotchilar, balki oʻz bemorlariga BMKI texnologiyasini taqdim etmoqchi boʻlgan shifokorlar uchun ham yoʻnalishni aniqlashda murakkabliklar tugʻdiradi. FDA (AQSh Oziq-ovqat va dori vositalari agentligi) BMKI tizimlarini meʼyoriy baholash boʻyicha yoʻl xaritasi ishlab chiqishda yetakchi rolni oʻz zimmasiga olgan. 2019-yil fevral oyida ular "Falajlangan yoki amputatsiya qilingan bemorlar uchun implantatsiya qilinadigan bosh miya-kompyuter interfeysi qurilmalari – noklinik sinovlar va klinik omillar" nomli loyiha koʻrsatmasini eʼlon qildi [106].

NeuroTech Network (http://www.neurotechnetwork.org) – bu notijorat tashkilot boʻlib, u neyrotexnologik mahsulotlar, jumladan BMKI tizimlari haqida axborot, kirish imkoniyati va xabardorlikni oshirishga xizmat qiladi. Shuningdek, u nogiron shaxslar uchun mavjud neyrotexnologiya turlari haqida bemorlar va tibbiy mutaxassislar uchun resurslar taqdim etadi. Clinicaltrials.gov sayti AQShdagi BMKI sohasidagi koʻpchilik ilmiy tadqiqotlarni aks ettiradi, biroq hozircha shifokorlar, bemorlar yoki ularning ishonchli shaxslari foydalanishi mumkin boʻlgan, doimiy ravishda yangilanib turuvchi, klinik jihatdan qoʻllanilishi mumkin boʻlgan IMK maʼlumotlar bazasi mavjud emas. Agar bunday resurs yaratilsa, u BMKI texnologiyalarining eng soʻnggi yutuqlariga kengroq kirishga imkon berishi mumkin boʻladi.

Foydalanuvchilarga moʻljallangan BMKI ilovalari va ularning klinik qoʻllanilishi.

Foydalanuvchilarga moʻljallangan bosh miya-kompyuter interfeysi dasturlarining paydo boʻlishi texnologiyalarni rivojlantirish uchun katta miqdorda investitsiyalarni jalb etish nuqtayi nazaridan foydali boʻlishi mumkin. Biroq, bu jarayon foydalanuvchilarni chalgʻitishi – yaʼni bu qurilmalar faqat tibbiy sharoitlarda samaradorlikni taʼminlay oladi degan notoʻgʻri tasavvurni uygʻotishi xavfi ham mumkin.

BMKI texnologiyalarini bemorlarga qoʻllashni istagan shifokorlar quyidagi uch toifadagi mahsulotlar haqida xabardor boʻlishlari kerak. Ular ishlab chiqish bosqichiga qarab quyidagicha tasniflanadi:

1. Klinik qoʻllanilishga ruxsat etilgan BMKI – ishlab chiqaruvchilar tomonidan taqdim etiladigan va klinik amaliyotda foydalanishga ruxsat olingan tizimlar.

2. Klinik tadqiqot bosqichidagi BMKI – hozirda faol klinik sinovlarda ishtirok etayotgan tizimlar.

3. Tajriba bosqichidagi BMKI – hali tadqiqot va laboratoriya rivojlantirish bosqichida boʻlgan tizimlar.

Klinik qoʻllanilishga ruxsat etilgan BMKI lar toifasi.

Bu toifaga harakat buzilishlari yoki epilepsiya bilan ogʻrigan bemorlar uchun moʻljallangan miya chuqur stimulyatsiyasi (DBS) tizimlari kiradi (2-rasm). Shuningdek, NeuroPace tizimi ham ushbu toifaga kiradi – u miya yuzasiga oʻrnatiladigan elektrokortikografik (ECoG) elektrodlardan foydalanib, epileptogen faollikni aniqlaydi va kutilayotgan tutqanoqlarni oldini olish uchun elektr impulslarini yuboradi.

Hozirda ochiq tipdagi DBS tizimlari FDA tomonidan tasdiqlangan, ammo yopiq siklli DBS tizimlari (yaʼni, neyromodulyator signallari miya faoliyatining qayd etilgan va dekodlangan signallariga asoslanadigan tizimlar) hali ham tadqiqot bosqichida. NeuroPace tizimining narxi taxminan 30 000-40 000 AQSh dollarini tashkil etadi va u epilepsiyaga qarshi jarrohlik amaliyoti tavsiya etilmagan, dori vositalariga chidamli fokal epilepsiya bilan ogʻrigan bemorlar uchun asosiy sugʻurta kompaniyalari tomonidan qoplanadi [107].

Bu borada bizning markazimizda, yaʼni Samarqand davlat tibbiyot universiteti huzuridagi Neyroxirurgiya va neyroreabilitatsiya ixtisoslashtirilgan ilmiy-amaliy markazida respublikamizda ilk marta 2023 yil dekabrda Parkinson kasalligida bosh miya chuqur tizimlariga DBS – BMKI tizimi muvaffaqiyatli oʼrnatildi va 2025 yil oktyabr oyigacha shu kabi nanotexnologiyali operatsiyalar 65 ta bemorlarda amalga oshirildi [108].

BMKI tizimining umumiy qiymatiga materiallar, jarrohlik oʻrnatish (zarur boʻlsa) va qoʻshimcha xizmatlar kiradi. Ammo hozircha BMKI uchun yagona sugʻurta yoki davlat toʻlov siyosati mavjud emas – bu esa tizim xarajatlarini individual holatlarda oʻzgaruvchan boʻlishiga sababdir [109].

Klinik qoʻllanilishga ruxsat etilgan neyrotexnologiyalar – BMKI sinfiga kiruvchi qurilmalardan tashqari, neyrotiklanish maqsadida qoʻllaniladigan boshqa texnologiyalarni ham oʻz ichiga oladi va bu kabi qurilmalar jumlasiga quyidagilar kiradi:

Mioelektrik ortozlar – amputatsiya yoki orqa miya shikastlanishi natijasida qoʻl-oyoq funksiyasini yoʻqotgan bemorlarda harakatni tiklash uchun;

Kiyiladigan robotlashtirilgan ekzoskeletonlar;

Koxlear implantlar – eshitish qobiliyatini tiklash uchun.

Ushbu maqolaning asosiy mavzusi ushbu texnologiyalar bo‘lmasa-da, shifokorlar ularning klinik amaliyotda mavjudligi va neyrotiklanishdagi foydasi haqida xabardor bo‘lishlari muhimligini ta’kidlamoqchimiz.

BMKI tomonidan tasdiqlangan dastlabki neyroprotezi.

BMKI tomonidan tasdiqlangan birinchi neyroprotezi NeuroControl Freehand tizimi bo‘lgan. U orqa miya jarohati olgan bemorlarda qo‘l funksiyasini tiklashga yordam bergan. Afsuski, mahsulot texnik jihatdan muvaffaqiyatli va foydalanuvchilar tomonidan yuqori baholangan bo‘lishiga qaramay, uning ishlab chiqarilishi hozirda to‘xtatilgan [104, 110].

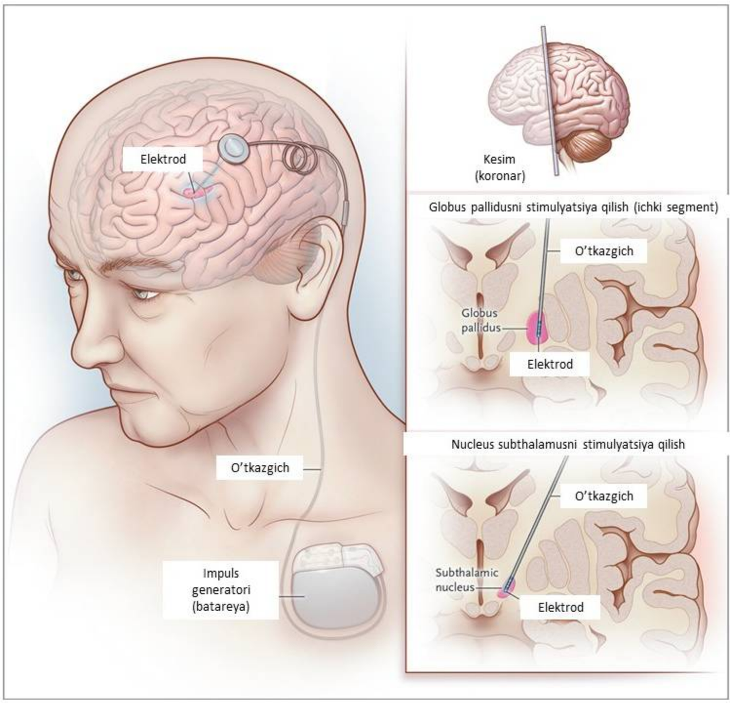
DARPA tomonidan moliyalashtirilgan DEKA LUKE qo‘l tizimi.

DEKA LUKE sun’iy qo‘l tizimi 2014-yilda FDA tomonidan klinik qo‘llanilishga ruxsat olgan. Bu tizim elektromiografik (EMG) elektrodlar yordamida foydalanuvchining harakat niyatini aniqlaydi va ushbu signallarni ko‘p erkinlik darajalariga ega murakkab harakatlarga aylantiradi. Tizimning narxi taxminan 150 000 AQSh dollarini tashkil etadi. U AQSh Veteranlar ishlari vazirligi tomonidan qoplanadi, ammo ko‘pchilik sug‘urta kompaniyalari tomonidan qoplanmaydi [111].

Bundan tashqari, neyromushakli protezlarning yangi turlari – masalan, suyakka mahkamlanadigan robotlashtirilgan qo‘l va yelkadagi nerv hamda mushaklarga implantatsiya qilingan elektrodlardan foydalanadigan modellari ishlab chiqilmoqda. Ular protez qo‘l bilan ikki yo‘nalishli (afferent va efferent) sensomotor aloqani ta’minlaydi va ayrim bemorlarda kundalik hayotda allaqachon qo‘llanilmoqda [112].

Robotlashtirilgan ekzoskeletonlar. Quyidagi FDA tomonidan tasdiqlangan robotlashtirilgan ekzoskeletonlar mavjud: ReWalk-ARGO Medical Technologies (Isroil), Ekso GT-Ekso Robotics (Kaliforniya), Indego-Parker Hannifin (Ogayo).

Bu tizimlar foydalanuvchiga kiyiladigan robot qo‘llab-quvvatlovchi tizimlar yordamida pastki oyoq-qo‘l harakatlarini boshlash imkonini beradi [113, 114]. ReWalk tizimining narxi taxminan 80 000 AQSh dollarini tashkil etadi va u AQSh Veteranlar uchun VA Choice dasturi orqali qoplanadi, ammo ko‘pchilik sug‘urta kompaniyalari tomonidan qoplanmaydi [115].



2-rasm. Bosh miya chuqur tizimlari stimulyatsiyasi (Deep brain stimulation - DBS) ishlashi sxematik tasviri

Ushbu qurilmadan foydalanish uchun quyidagi talablar mavjud [116]: Orqa miya shikastlanishi bo‘lishi, bo‘y uzunligi 160–190 sm oralig‘ida, tana vazni 100 kg dan kam, suyak zichligi me’yoriy, og‘ir spastiklik, kognitiv buzilishlar yoki boshqa og‘ir nevrologik kasalliklar bo‘lmasligi kerak. Ekso GT esa insultdan so‘ng reabilitatsiya uchun FDA tomonidan tasdiqlangan birinchi ekzoskeleton hisoblanadi [117-118]. Bu mahsulotlarni ishlab chiqaruvchi kompaniyalar, rasmiy distribyutorlar yoki maxsus o‘quv markazlari tarmoqlari orqali olish mumkin. Ularning to‘liq ro‘yxati internetda mavjud [113, 114, 116].

Klinik tadqiqot bosqichidagi BMKI lar.

Klinik darajadagi BMKI tizimlaridan foydalanayotgan bemorlarning aksariyati hozircha klinika sinovlari doirasida qatnashmoqda. 2019-yil may holatiga ko‘ra, 93 ta rasmiy ro‘yxatdan o‘tgan Bosh miya-kompyuter interfeysi loyihasi mavjud edi. Shifokorlar www.clinicaltrials.gov saytiga kirib, tadqiqot turi, tanlash mezonlari va o‘tkazilish joyi bo‘yicha qidiruv orqali bemor uchun mos klinik sinovlarni topishlari, shuningdek tadqiqot koordinatori bilan bog‘lanish uchun aloqa ma’lumotlarini olishlari mumkin. Agar bemor tanlov mezonlariga mos deb topilsa, tadqiqot koordinatori bemor va uning oila a’zolari bilan birgalikda klinik sinovga qo‘shilish uchun zarur bosqichlarni tashkil etadi.

BMKI texnologiyalarining tadqiqot yo‘nalishlari.

Klinik sinov bosqichidagi BMKI tizimlari turli texnologik yondashuvlarni o‘z ichiga oladi. Neyroreabilitatsiya kontekstida BMKI lar quyidagilarni qamrab oladi: muloqot (kommunikatsiya) funksiyasini tiklash texnologiyalari; harakat va mobil funksiyalarni tiklash tizimlari; uyqu, ong darajasi va kognitiv funksiyalarni yaxshilash texnologiyalari; shuningdek, vegetativ funksiyalarni (oshqozon-ichak, siydik pufagi va jinsiy faoliyat) tiklashga qaratilgan usullar. Bemorlar, ularning oilalari va shifokorlar kelajakda neyrotiklanish yondashuvlariga ta’sir ko‘rsatishi mumkin bo‘lgan istiqbolli BMKI texnologiyalari haqida xabardor bo‘lishlari lozim. Bu nafaqat realistik kutilmalarni shakllantirishga, balki og‘ir nevrologik shikastlanishdan so‘ng paydo bo‘lishi mumkin bo‘lgan “terapevtik befarqlik” (nihilizm) holatlariga qarshi kurashishga ham yordam beradi.

Shuningdek, mavjud va yangi BMKI texnologiyalarni bilish bemorlar, ularning oilalari va shifokorlar tomonidan ilmiy asoslangan qarorlar qabul qilishni osonlashtiradi [119].

Tadqiqot faoliyatlari va yangi yutuqlar.

Hozirda ko‘plab ilmiy guruhlar BMKI texnologiyalarini hayvonlar va odamlarda faol ravishda o‘rganmoqda va takomillashtirmoqdalar, jumladan so‘nggi yillarda aloqa tiklashga qaratilgan BMKI tizimlarida muhim yutuq – bu chuqur oʻrganish (deep learning) usullarini qoʻllash orqali miya yuzasiga oʻrnatilgan elektrokortikografik (ECoG) implantlardan olingan neyron signallarni inson eshita oladigan nutqqa aylantirish imkonining yaratilganidir [77, 78].

BMKI texnologiyalarining klinik amaliyotga oʻtishidagi muammolar va yechimlar. BMKI texnologiyalarining ulkan salohiyatiga qaramay, ilmiy, texnik, klinik, axloqiy va iqtisodiy omillar ularning klinik amaliyotga toʻliq kirib borishini cheklab turibdi. Muhandislik nuqtai nazaridan, implantatsiya qilingan sensorlarning signallarni barqaror va ishonchli aniqlash qobiliyati vaqt oʻtishi bilan pasayishi mumkin [120]. Bunga quyidagi omillar sabab boʻladi: reaktiv glioz (miya hujayralarining himoyaviy koʻpayishi) [121]; yalligʻlanish jarayonlari [122], mikroharakatlar yoki mexanik shikastlanishlar [123]; yoki impedans (elektr qarshilik) oʻzgarishlari, bu esa implantatsiya davomida asta-sekin kuchayadi [124–129]. Ushbu omillarning har biri sezuvchanlikning pasayishiga qancha hissa qoʻshishi aniq emas, ammo ularning taʼsiri oylar yoki hatto yillar davomida asta-sekin namoyon boʻladi.

Biroq, soʻnggi yillarda materiallar kimyosi, kompyuter modellashtirish va nanotexnologiyalar sohalaridagi yutuqlar tufayli ilgari ishlatilgan materiallardagi kamchiliklarni bartaraf etuvchi, mustahkam va chidamli sensorlar ishlab chiqilmoqda [130–132].

Sensorlarni kalibrlash va signallarni mashinali oʻrganish *(machine learning)* usullari yordamida dekodlashdagi yutuqlar bilan birgalikda, ushbu ilmiy taraqqiyotlar yaqin yillarda yanada ishonchli, bardoshli va aniq bosh miya-kompyuter interfeyslari yaratilishini bashorat qilmoqda. Ammo hatto samarali, xavfsiz va foydali texnologiya ishlab chiqilgan taqdirda ham, agar maqsadli bemor guruhi kichik yoki moliyaviy jihatdan taʼminlanmagan boʻlsa, uning keng joriy etilishi iqtisodiy jihatdan oʻzini oqlamasligi mumkin. Bu, ayniqsa, texnologiyani oʻrnatish va qoʻllab-quvvatlash uchun koʻp tarmoqli (multidisiplinar) jamoa zarurligini hisobga olganda, katta xarajatlarni keltirib chiqaradi.Bunga misol sifatida NeuroControl Freehand tizimini keltirish mumkin – u orqa miya jarohati olgan bemorlarda qoʻl harakat funksiyasini tiklashga muvaffaq boʻlgan, biroq 1998-yilda texnik jihatdan muvaffaqiyatli boʻlishiga qaramay, ishlab chiqarishdan toʻxtatilgan [104]. Bu kabi toʻsiqlar ayniqsa implantatsiya qilinadigan BMKI tizimlarida yanada kuchliroq namoyon boʻladi.

Shu omillarni va bosh miya-kompyuter interfeysi texnologiyalarining sogʻliqni saqlashdagi muhim ehtiyojlarni qondirish imkonini eʼtiborga olgan holda, AQSh Oziq-ovqat va farmatsevtika idorasining (FDA) Qurilmalar va radiologik sogʻliq markazi (CDRH) quyidagi yangi mexanizmlarni joriy etgan: tezlashtirilgan kirish (accelerated access), samarali koʻrib chiqish tizimi (shu jumladan, CMS bilan qoʻshma ekspertiza mexanizmi) va ariza topshirishdan oldingi baholash tizimi.

Bu mexanizmlar ishlab chiqish jarayonini soddalashtirish, klinik qoʻllanishga oʻtish jarayonini tezlashtirish, shu bilan birga bemorlar xavfsizligini taʼminlash maqsadida ishlab chiqilgan [104, 106]. Klinik nuqtai nazardan, koʻplab bemorlar va shifokorlar hali ham IMK tizimlari va ularni amaliyotda qoʻllash imkoniyatlari haqida amaliy bilimga ega emaslar (133).

Bosh miya-kompyuter interfeysi oʻrnatilgan bemorlar bilan faol ishlaydigan shifokorlar uchun davolash natijalarini baholash koʻrsatkichlari va bemorning qoniqish darajasini aniqlash usullari koʻp hollarda aniq va shaffof boʻlmasligi mumkin. Dasturchilar, shifokorlar, bemor huquqlarini himoya qiluvchi tashkilotlar va boshqa manfaatdor tomonlar oʻrtasidagi yaqin hamkorlik klinik natijalar mezonlarini aniqlashtirishda, bemorlar ehtiyojlarini inobatga olishda, xavf va foyda oʻrtasidagi muvozanatni optimallashtirishda, shuningdek sogʻliqni saqlash tizimiga taʼsirini kuchaytirishda muhim rol oʻynaydi. Shifokorlar BMKI ni tavsiya qilishdan oldin, bu bemorni maxsus markazga yoʻnaltirish yoki soha mutaxassisi bilan maslahatlashishni talab qilishi mumkinligini hisobga olib, bemorlar va ularning qarovchilari kutayotgan natijalar real ekanligiga ishonch hosil qilishlari kerak.

Bu jarayon quyidagilarni oʻz ichiga olishi lozim: tanlanayotgan BMKI tizimining xavflari, afzalliklari, va potensial kamchiliklari haqida batafsil maʼlumotlar [134]. Sugʻurta kompaniyalari va davlat dasturlari oʻrtasida BMKI uchun yagona toʻlov siyosati mavjud emasligi sababli, hozirgi narxlar ularning amaliyotga joriy etilishiga toʻsqinlik qilishi mumkin [109, 135]. Agar BMKI sugʻurta tashkiloti tomonidan qoplanmasa, bemorlar xarajatlarni mustaqil toʻlashga majbur boʻlishlari mumkin; ayrim hollarda ular bu maqsadda tibbiy kraudfanding (aholining ixtiyoriy mablagʻ toʻplashi) yoʻliga murojaat qilishlari, bu esa axloqiy va ijtimoiy muammolarni keltirib chiqarishi mumkin [136].

Shu sababli, ushbu toʻsiqlarni hisobga olgan holda, BMKI texnologiyalariga moliyaviy va teng imkoniyatli kirishni taʼminlash uchun yagona va adolatli kompensatsiya siyosatini ishlab chiqish zarur. Bunday siyosatni ishlab chiqish, shubhasiz, BMKI hatto kichik bemorlar guruhida ham barqaror va ishonchli foyda keltirishi isbotlangach, ancha osonlashadi. Bunga NeuroPace BMKI tizimining ishlab chiqilishi va amaliyotga joriy etilishi misol boʻla oladi [137].

BMKI texnologiyalari takomillashib borar ekan, axloqiy masalalar tobora dolzarb ahamiyat kasb etadi. Ular quyidagilarni oʻz ichiga oladi: bemorning ishtiroki va javobgarligi [138]; qaror qabul qilish qobiliyati [139]; shaxsiy identifikatsiya (shaxsiyat shakllanishi) [140]; maxfiylik [133, 141, 142]; neyron maʼlumotlarni saqlash va ulashish [143]; biologik imkoniyatlarni yaxshilashga qaratilgan qoʻllanmalar [144]; texnologiyalarga teng kirish imkoniyatidagi farqlar [145]; ilmiy-tadqiqot etikasiga oid muammolar [146]. Ushbu masalalarni oldindan tahlil qilish va ehtiyotkorlik bilan baholash, BMKI tizimlarini ishlab chiqishning barcha bosqichlarida bioetika ijrosini taʼminlashga, shuningdek, neyroreabilitatsiya amaliyotiga muvaffaqiyatli joriy etilishiga yordam beradi [147-149].

Xulosa. Bosh miya-kompyuter interfeyslari nevrologik kasalliklarga chalingan bemorlarning, xususan kranioserebral travmalarning oqibatlaridagi neyrosturuktur va funksional tiklanishini taʼminlashda ulkan salohiyatga ega. Ular nevrologik shikastlanish yoki kasallik natijasida yoʻqotilgan funksiyalarni tiklash yoki neyron plastiklikni ragʻbatlantirish orqali oʻrganish va xotira qayta taqsimlanishini yaxshilash imkonini beradi.

BMKI tizimlarining butun sikli – dastlabki loyihalash va tadqiqotlardan boshlab, klinik sinovlar, tartibga soluvchi organlarning roziligi va klinik amaliyotga joriy etilishigacha – koʻplab toʻsiqlar va imkoniyatlarni oʻz ichiga oladi. Nevrologik buzilishlarga ega bemorlar bilan ishlovchi shifokorlar BMKI texnologiyalarining hozirgi rivojlanish bosqichlari haqida xabardor boʻlishlari, hamda ularni bemor ehtiyojlariga moslashtirishni bilishlari zarur. Shuningdek, tadqiqotchilar, muhandislar, shifokorlar, bemor huquqlarini himoya qiluvchilar, tartibga soluvchi organlar, bioetika mutaxassislari, sugʻurta kompaniyalari va boshqa manfaatdor tomonlar oʻrtasidagi doimiy hamkorlik – BMKI texnologiyalarining neyroreabilitatsiya sohasidagi imkoniyatini amalda joriy qilish va uning barqaror rivojlantirishda hal qiluvchi omil boʻladi.

BMKI texnologiyalarining bugungi kunda xorijiy mamlakatlar sog’liqni saqlash tizimi amaliyotiga faol tadbiq etilayotganligiga qaramasdan, hozirgacha bizda, ya’ni O’zbekiston Respublikasi sog’liqni saqlash tizimida [108], xususan kranioserebral travmalar oqibatlarida va boshqa turdagi nevrologik kasalliklardagi neyrofunksional yetishmovchiliklarida keng qo’llanilmasdan qolayotganligi bu borada yangi yondashuvlar va faol chora-tadbirlar ishlab chiqilishi hamda ular tizimli amalga oshirilishi lozimligini anglatadi.

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