

Wiku Andonotopo*, Muhammad Adrianes Bachnas, Julian Dewantiningrum, Mochammad Besari Adi Pramono, I Nyoman Hariyasa Sanjaya, Ernawati Darmawan, Muhammad Ilham Aldika Akbar, Dudy Aldiansyah, Cut Meurah Yeni, Nuswil Bernolian, Sri Sulistyowati, Waskita Ekamaheswara Kasumba Andanaputra, Milan Stanojevic and Asim Kurjak

Revisiting KANET in the context of fetal connectomics: defining optimal gestational windows for neurodevelopmental screening

<https://doi.org/10.1515/jpm-2025-0234>

Received May 2, 2025; accepted September 23, 2025;

published online November 26, 2025

Abstract

Objectives: To introduce the KANET-connectome matrix (KANET-Con) as a conceptual framework linking fetal

behaviors observed on four-dimensional (4D) ultrasound to underlying neural network maturation, and to evaluate optimal gestational timing for functional neurodevelopmental screening.

Methods: A narrative review was conducted using a PRISMA-guided literature identification and screening process. PubMed, Scopus, and Web of Science were searched (January 2000–March 2025) for studies addressing fetal connectomics, fetal neurobehavior, KANET scoring, and developmental neuroimaging. Forty-two peer-reviewed studies met inclusion criteria. Observed fetal behaviors—including facial mimicry, eye blinking, limb movement, and overall gestalt coordination—were aligned with their most plausible neural substrates using evidence from developmental neuroscience and imaging.

Results: Findings demonstrated clear temporal associations between specific fetal behaviors and neural circuit development. Eye blinking and facial expressions (24–26 weeks) correlated with brainstem-cortical integration; hand-to-face gestures (26–30 weeks) reflected emerging interhemispheric pathways; and complex limb coordination (28–32 weeks) was linked to corticospinal and basal ganglia maturation. Collectively, these data indicate that 24–32 weeks of gestation represents an optimal window for KANET-based neurobehavioral screening. Additionally, emerging artificial intelligence applications show potential to enhance scoring objectivity by detecting subtle movement features such as behavioral entropy, asymmetry, and latency.

Conclusions: KANET, interpreted through a fetal connectomic lens, provides a functional window into early neural integration. The KANET-Con offers a clinically relevant, globally accessible conceptual model to support early detection of neurodevelopmental deviations and inform risk stratification, particularly in resource-limited settings.

Keywords: fetal connectome; KANET; prenatal neurodiagnostics; 4D ultrasound; fetal behavior

*Corresponding author: Wiku Andonotopo, MD, PhD, Fetomaternal Division, Department of Obstetrics and Gynecology, Women Health Center, Ekahospital BSD City, Serpong, Tangerang, Banten, Indonesia, E-mail: wiku.andonotopo@gmail.com. <https://orcid.org/0000-0001-9062-8501>

Muhammad Adrianes Bachnas and Sri Sulistyowati, Fetomaternal Division, Department of Obstetrics and Gynecology, Medical Faculty of Sebelas Maret University, Dr. Moewardi Hospital, Surakarta, Indonesia. <https://orcid.org/0000-0002-1710-3909> (M.A. Bachnas)

Julian Dewantiningrum and Mochammad Besari Adi Pramono, Fetomaternal Division, Department of Obstetrics and Gynecology, Medical Faculty of Diponegoro University, Dr. Kariadi Hospital, Semarang, Indonesia

I Nyoman Hariyasa Sanjaya, Fetomaternal Division, Department of Obstetrics and Gynecology, Faculty of Medicine Universitas Udayana, Prof. dr. I.G.N.G Ngoerah General Hospital, Bali, Indonesia

Ernawati Darmawan and Muhammad Ilham Aldika Akbar, Maternal-Fetal Medicine Division, Department of Obstetrics and Gynecology, Faculty of Medicine Universitas Airlangga, Dr. Soetomo Hospital, Surabaya, Indonesia

Dudy Aldiansyah, Fetomaternal Division, Department of Obstetrics and Gynecology, Faculty of Medicine, Universitas Sumatera Utara, H. Adam Malik General Hospital, Medan, Sumatera Utara, Indonesia

Cut Meurah Yeni, Maternal-Fetal Medicine Division, Department of Obstetrics and Gynecology, Faculty of Medicine Universitas Syiah Kuala, Dr. Zainoel Abidin General Hospital, Aceh, Indonesia

Nuswil Bernolian, Maternal-Fetal Medicine Division, Department of Obstetrics and Gynecology, Faculty of Medicine Universitas Sriwijaya, Dr. Mohammad Hoesin General Hospital, Palembang, Indonesia

Waskita Ekamaheswara Kasumba Andanaputra, Department of Medicine, Undergraduate Program in Medical Science, Faculty of Medicine, Padjajaran University, Bandung, West Java, Indonesia. <https://orcid.org/0009-0009-2181-3442>

Milan Stanojevic, Department of Neonatology and Rare Diseases, Medical University of Warsaw, Warsaw, Poland

Asim Kurjak, Department of Obstetrics and Gynecology, Medical School University of Zagreb, Zagreb, Croatia

Introduction

The architecture of the human brain begins to form long before birth. Within the intrauterine environment, neurons proliferate, migrate, and establish intricate connections, giving rise to the fetal connectome—a foundational blueprint of functional neural networks that support movement, sensation, emotion, and cognition *in utero* [1–3]. This highly coordinated neurodevelopmental process unfolds in tandem with emerging fetal behaviors, which manifest as spontaneous movements and increasingly complex gestures detectable by modern imaging technologies [4, 5].

Recent advancements in fetal magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI) have mapped key neural circuits, including thalamocortical pathways, cortico-cerebellar loops, and interhemispheric bridges—many of which emerge by the mid-second trimester and coincide with the appearance of specific motor and facial behaviors [2, 6–11, 22]. For example, the maturation of thalamocortical projections between 24 and 28 weeks of

gestation is temporally aligned with facial mimicry, eye blinking, and hand-to-face gestures [10, 21, 24, 26, 28] (Figure 1).

Despite their value, MRI and DTI are limited by high cost, motion sensitivity, and restricted accessibility—particularly in low- and middle-resource settings [3, 11, 25]. By contrast, ultrasonography—especially in its four-dimensional (4D) format—provides a real-time, non-invasive, and widely accessible method for fetal assessment. The Kurjak antenatal neurodevelopmental test (KANET), introduced in the early 2000s, uses 4D ultrasound to evaluate fetal behavior via a structured scoring system [4, 5, 12, 13] (Table 1). It captures dynamic features such as general movements, limb coordination, facial expressions, and blinking—parameters shown to predict postnatal neurodevelopmental outcomes, particularly in high-risk pregnancies [17–19, 25].

Nonetheless, a conceptual gap persists. KANET, although widely utilized, is often interpreted as a catalog of isolated motor activities rather than as an index of coordinated neural function. Contemporary systems neuroscience suggests fetal behavior is not random but reflects observable signatures of developing neural systems [6, 14–16, 20, 22, 24, 26, 28–30, 33] (Figures 2–4). Movements such as yawning, facial grimacing, or hand-to-hand contact may represent maturation of discrete brain circuits, including corticospinal tracts, brainstem nuclei, subplate zones, and interhemispheric fibers.

This review addresses whether fetal behavior can serve as a functional proxy for developing neural networks. We introduce the KANET-connectome matrix (KANET-Con), a hypothesis-generating conceptual framework mapping each KANET behavior to its most likely neural substrate. This model integrates developmental neuroscience, fetal imaging, and behavioral ontogeny [1–3, 6–11, 14, 20–24, 26, 30–32, 36, 38–41] and contextualizes behavioral expression relative to gestational neurocircuit milestones. Our objective is to reinterpret KANET-derived behavioral data through the lens of fetal connectome development and to identify optimal gestational windows for neurodevelopmental screening (Table 2), providing a theoretical scaffold for future clinical interpretation and research [7, 8, 10, 11, 34–37, 42–45].

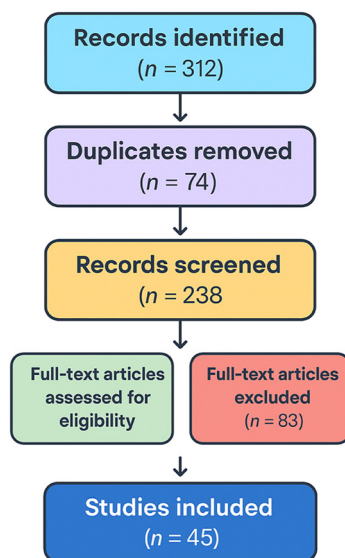


Figure 1: PRISMA 2020 flow diagram of literature selection process. This figure outlines the structured methodology used to identify and select studies included in this review, following PRISMA 2020 guidance. A total of 312 records were retrieved from PubMed, Scopus, and Web of Science. After removal of 74 duplicates, 238 records were screened by title and abstract, with 110 excluded due to irrelevance, lack of behavioral or connectomic focus, or insufficient methodological rigor. The remaining 128 full-text articles were assessed for eligibility, and 83 were excluded for reasons including narrative-only format, animal-only studies, absence of fetal neurobehavioral analysis, or limited methodological transparency. The final synthesis included 45 original studies, encompassing 4D ultrasound, fetal MRI/DTI, and AI-enhanced behavioral analysis, which together formed the evidence base for developing the KANET-Connectome framework.

Materials and methods

Study design

This work was designed as an integrative narrative review of the published literature in fetal connectomics and behavioral sonography. It did not involve the recruitment of new

Table 1: Key literature comparison table.

Authors	Year	Journal	Insights	Strengths	Limitations	Primary mode of study
Kostović & Jovanov-Milošević [1]	2006	Semin Fetal Neonatal Med	Defined timeline for development of cerebral connections <i>in utero</i> .	Foundational neuro-developmental staging across gestation.	Limited functional-behavioral correlation.	Other
Kurjak et al. [4]	2008	J Perinat Med	Introduced KANET as a structured behavioral test using 4D ultrasound.	Practical, low-cost assessment for prenatal neurodevelopment.	Observer-dependent; lacks neural substrate mapping.	4D ultrasound
Tymofiyeva et al. [3]	2012	PLoS One	DTI-based mapping of structural connectome without templates.	Revealed individual variability in fetal brain maturation.	Lacked integration with behavioral observation.	DTI
Stanojevic et al. [14]	2012	Semin Fetal Neonatal Med	Demonstrated behavioral continuity from fetal to neonatal periods.	Empirical validation of KANET’s developmental relevance.	Relatively short-term neonatal follow-up.	Other
Thomason et al. [2]	2014	PLoS One	Graph-theoretical analysis of fetal brain networks via fMRI.	Pioneering demonstration of functional connectivity in fetuses.	Small sample size; motion artifacts affect fMRI precision.	fMRI
Song et al. [10]	2017	Front Neurosci	Mapped fetal structural connectome across mid to late gestation.	Robust tracking of white matter tract maturation.	Did not address functional connectivity or fetal behavior.	DTI
Scheinost et al. [16]	2017	Pediatr Res	Explored prenatal stress impacts on fetal connectome.	Environment–connectome interactions shown <i>in utero</i> .	No integration with structured behavior scales.	fMRI
Krontira & Cruceanu [15]	2020	J Neurosci	Early maturing networks linked to future functional domains.	Conceptual framing for connectomic timing relevance.	Primarily theoretical; limited empirical data.	Other
De Asis-Cruz et al. [9]	2021	Cereb Cortex	Showed global network organization in the fetal brain.	Connectomics-based correlation with gestational age.	No behavioral data integration.	fMRI
Carroll et al. [33]	2021	Neuroscientist	Reviewed link between abnormal connectivity and autism.	Bridge between fetal neuroscience and neurodevelopmental disorders.	Review format; lacked direct fetal data.	Other
Kim et al. [20]	2023	Cereb Cortex	Modeled gestational-age-related changes in connectivity patterns.	High-resolution connectomic analysis over time.	Not behaviorally anchored; MRI-based only.	fMRI
Taymourtash et al. [21]	2023	Cereb Cortex	Detailed maturation of thalamocortical and cortico-cortical connections.	Granular network-specific maturation timelines.	Focused on connectivity without behavior linkage.	fMRI
Bachnas et al. [34]	2024	J Perinat Med	AI-enhanced analysis of fetal facial behavior via 4D ultrasound.	Enabled objective behavioral tracking and classification.	Still in early validation phases.	4D ultrasound + AI
Andonotopo et al. [35]	2025	J Perinat Med	Merged behavioral output with high-res modeling using AI frameworks.	Merged behavioral output with high-res modeling.	AI tools require clinical validation and scalability testing.	4D ultrasound + AI

The table presents a comparative summary of foundational studies underpinning the conceptual and methodological framework of this review. The primary mode of study indicates whether the publication utilized 4D ultrasound, fMRI, DTI, AI-enhanced analysis, or other methodologies.

clinical subjects or experimental interventions; therefore, Institutional Review Board approval was not required. The purpose was to synthesize existing data and develop a conceptual framework—the KANET-Con—that maps fetal

behaviors observed through the KANET to their most plausible neural circuits. The approach follows a structured format appropriate for an original research-style article while remaining hypothesis-generating in nature.

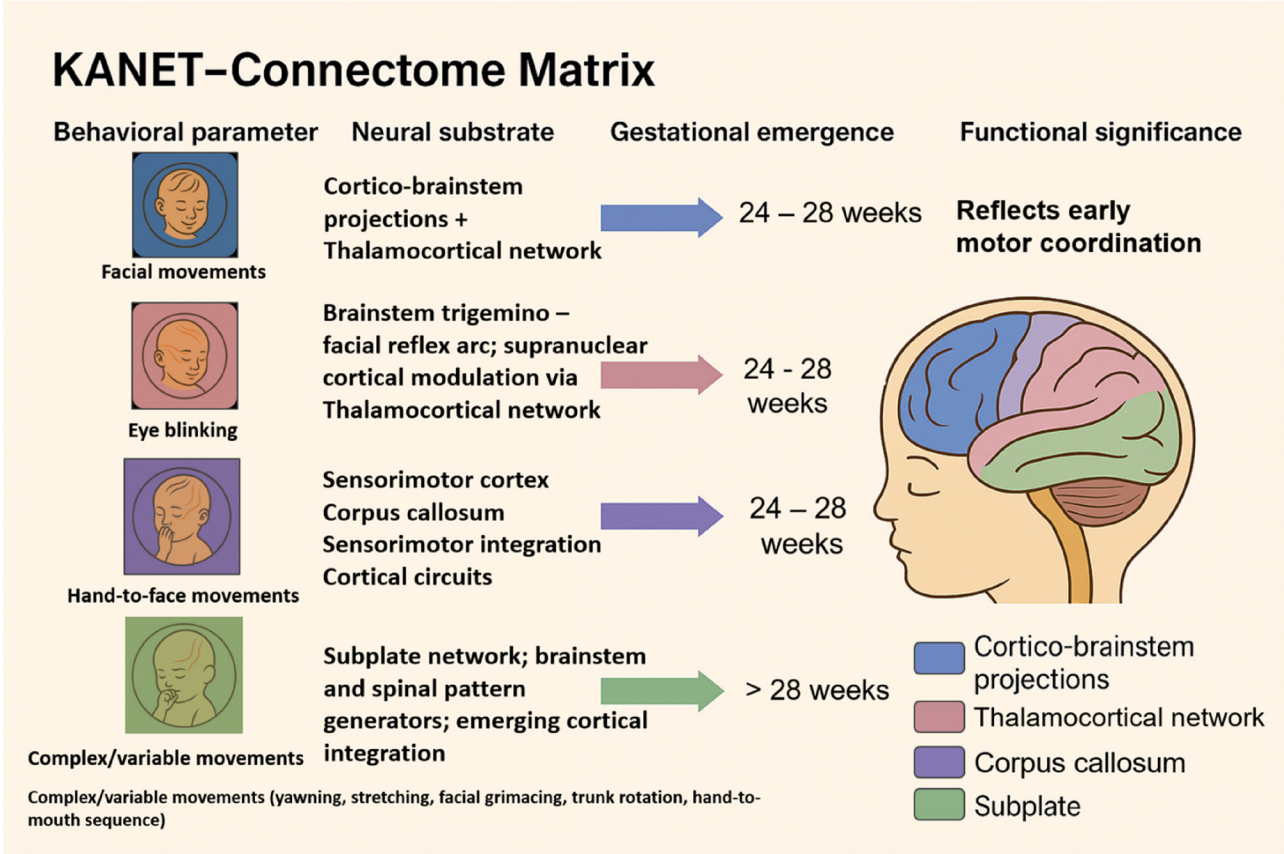


Figure 2: KANET-connectome matrix: linking fetal motor behaviors to neural network maturation. This schematic integrates the Kurjak antenatal neurodevelopmental test (KANET) behavioral parameters with their underlying neural substrates, gestational emergence windows, and functional significance. Four representative fetal behaviors—facial movements, eye blinking, hand-to-face movements, and complex/variable movements—are mapped to specific brain structures and networks involved in their generation. Color coding corresponds to key neuroanatomical systems: Cortico-brainstem projections (blue), thalamocortical network (pink), corpus callosum (purple), and subplate (green). The timeline reflects the typical onset of each behavior in weeks of gestation, highlighting the progressive integration of subcortical and cortical pathways during late mid-gestation. Complex/variable movements include yawning, stretching, facial grimacing, trunk rotation, and hand-to-mouth sequences.

Literature search and selection

A structured literature search was performed across three major academic databases: PubMed, Scopus, and Web of Science. The search included studies published between January 2000 and March 2025, reflecting a period of significant advancement in fetal brain connectomics and prenatal behavioral assessment. Boolean logic was applied to combine Medical Subject Headings (MeSH) and free-text terms, including “fetal behavior,” “fetal movement,” “Kurjak,” “connectome,” “neural connectivity,” “MRI,” “DTI,” and “4D ultrasound.” Reference lists of relevant articles were manually searched to identify additional eligible studies.

Studies were eligible if they involved human fetal subjects and addressed at least one of the following: ultrasound-based fetal behavioral assessment, fetal connectome development using advanced neuroimaging, or analytical frameworks linking fetal movement to neural circuit maturation. Studies that were purely opinion-based, case reports lacking conceptual interpretation, or exclusively animal-focused (except when serving as comparative behavioral evidence) were excluded. Screening was conducted in two stages, beginning with title and abstract review and followed by full-text evaluation for conceptual relevance. This structured approach yielded 45 original studies, all of which informed the synthesis and conceptual

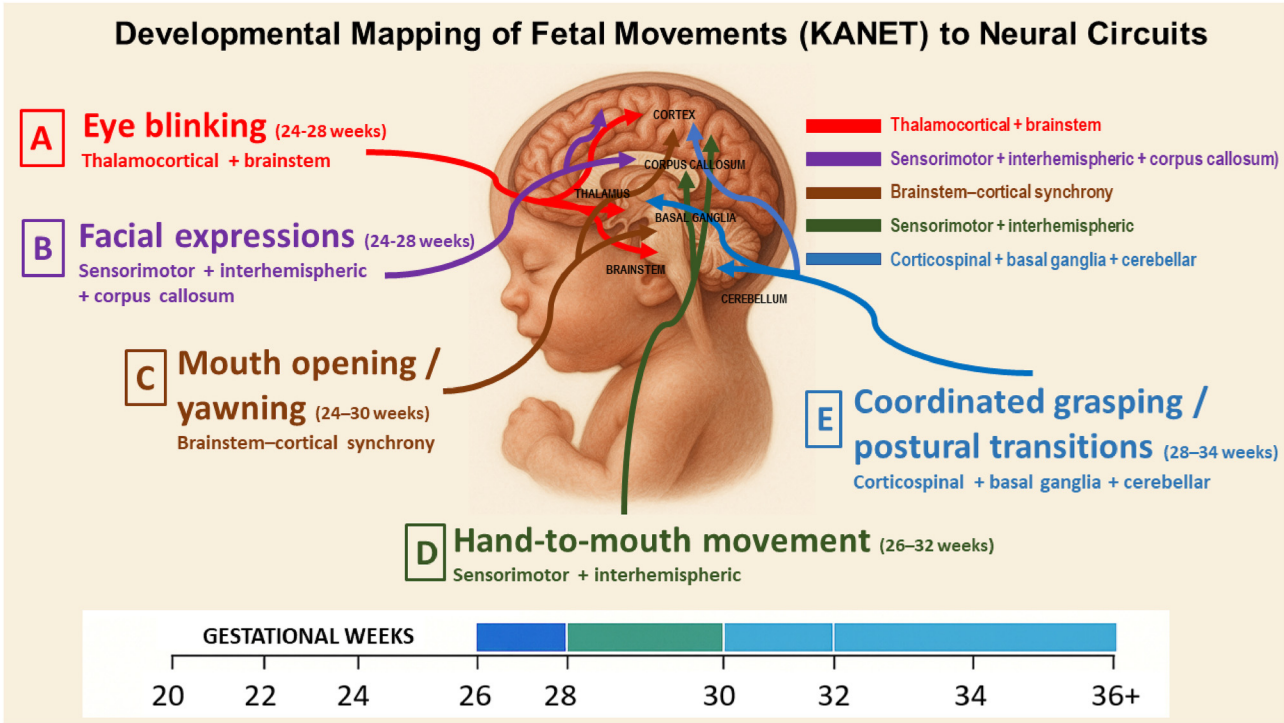


Figure 3: Developmental mapping of fetal movements (KANET) to neural circuits and gestational age. Five key fetal movements (A–E) are shown with their developmental windows and neural substrates. (A) Eye blinking (24–28 weeks, thalamocortical + brainstem, red). (B) Facial expressions (24–28 weeks, sensorimotor + interhemispheric + corpus callosum, purple). (C) Mouth opening/yawning (24–30 weeks, brainstem–cortical synchrony, brown). (D) Hand-to-mouth movement (26–32 weeks, sensorimotor + interhemispheric, green). (E) Coordinated grasping/postural transitions (28–34 weeks, corticospinal + basal ganglia + cerebellar, blue). Bottom timeline shows onset periods with color-coded bars.

modeling process. The flow of literature identification, screening, and inclusion is summarized in Figure 1.

Data extraction and synthesis

For each included study, information was extracted regarding authorship, publication year, population studied, gestational age range, imaging modality, and major findings. These data are summarized in Table 1, which now includes an additional column specifying the primary mode of investigation—such as 4D ultrasound, MRI, DTI, or artificial intelligence (AI)–assisted movement analysis—and arranges studies in chronological order as recommended by peer review.

Thematic synthesis focused on identifying relationships between fetal behaviors—such as facial expressions, hand-to-face gestures, eye blinking, and yawning—and underlying neural circuits, including thalamocortical projections, cortico-cerebellar loops, interhemispheric pathways, and

basal ganglia integration. These relationships are consolidated in the **KANET-connectome matrix** (Table 2), which aligns behavioral parameters with their likely neuroanatomical substrates, and in the gestational timing chart, which illustrates the developmental onset of specific behaviors relative to known neurocircuit milestones. Additional tabular summaries describe the application of AI techniques to enhance fetal movement assessment (Table 3), compare KANET with MRI- and DTI-based approaches (Table 4), and demonstrate the use of KANET in diverse clinical risk scenarios (Table 5).

Conceptual framework and supporting figures

Conceptual modeling was informed by developmental neuroscience, fetal imaging data, and ultrasound-based neurobehavioral observations. Visual representations were developed to aid interpretation and clinical translation,

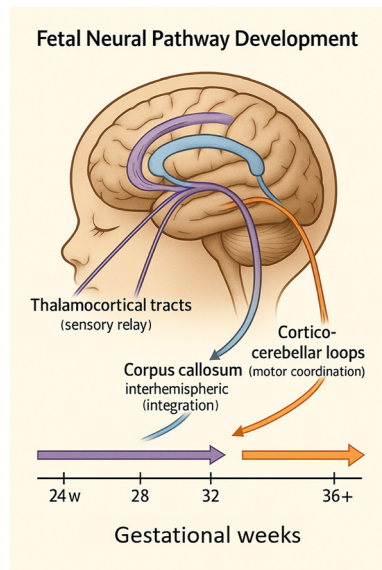


Figure 4: Developmental emergence of key fetal brain pathways supporting neurobehavior. This schematic illustrates the sequential maturation of three critical neural pathways that underpin fetal neurobehavioral development, aligned with gestational timing. Thalamocortical tracts (purple) emerge by ~24–28 weeks, enabling early sensory relay and integration. Interhemispheric fibers through the corpus callosum (blue) develop by ~28–32 weeks, supporting bilateral coordination and cross-hemispheric integration of motor and sensory activity. Cortico-cerebellar loops (orange) mature later, after ~32 weeks, establishing reciprocal communication between motor cortex and cerebellum essential for refined motor control and coordination. The combined maturation of these pathways forms the structural basis for increasingly complex fetal behaviors, as assessed by the kurjak antenatal neurodevelopmental test (KANET), and highlights how neural network synchronization progresses toward late gestation.

including neural circuit timelines and behavior-to-structure mappings (Figures 2–4), a radial schema of connectome–behavior associations (Figure 3), and a proposed clinical workflow integrating AI-assisted scoring and risk stratification prior to targeted intervention. Collectively, these visual tools support the integrative nature of the proposed KANET-connectome framework.

Critical appraisal

The included studies exhibited heterogeneity in study design, sample size, imaging modality, and behavioral scoring methodology. Despite these differences, a clear convergence emerged: fetal behaviors assessed by KANET demonstrated temporal associations with critical phases of neural circuit development documented by fetal neuroimaging. This observation supports the central premise of this review that structured behavioral ultrasound, when interpreted through the

lens of fetal connectomics, may provide a non-invasive functional perspective of the developing fetal brain. The findings offer a theoretical platform for future empirical validation and refinement of fetal neurofunctional assessment.

Results

Literature selection and study characteristics

A structured literature search identified 312 records from PubMed, Scopus, and Web of Science. After the removal of 74 duplicates, 238 records underwent title and abstract screening, resulting in the exclusion of 110 articles for thematic irrelevance or insufficient methodological detail. Full-text evaluation of 128 studies led to the exclusion of 86 for reasons including non-human focus, narrative or opinion-only format, or lack of direct neurobehavioral interpretation. The final synthesis included 45 original studies relevant to fetal neurobehavior, connectomics, and emerging AI applications (Figure 1).

Among these, **26 studies** focused on 3D or 4D ultrasound and the KANET, examining parameters such as spontaneous limb movements, facial expressions, eye blinking, and hand-to-face gestures [4, 5, 12, 13, 17–19, 25]. **Twelve studies** employed fetal MRI or DTI to map structural and functional brain connectivity [2, 3, 6–11, 20–24], while **four studies** incorporated AI methodologies, including convolutional neural networks for fetal facial expression analysis and micro-movement quantification [34–36]. Gestational age windows between 24 and 32 weeks were most frequently represented, coinciding with critical phases of thalamocortical and corticospinal integration (Table 1).

Behavioral parameters and neural circuit mapping

Behaviors evaluated using KANET—such as blinking, facial mimicry, limb flexion-extension, hand-to-face contact, and general movement fluidity—were consistently linked to neural circuit development. Oculomotor and facial behaviors emerging between 24 and 28 weeks were associated with cranial nerve nuclei activation, reticular formation activity, and supranuclear control pathways [1, 4, 5, 12, 26]. Limb coordination and posture transitions mirrored corticospinal tract maturation, basal ganglia loop refinement, and interhemispheric synchronization via the corpus callosum [6, 10, 22, 24].

Table 2: Combined KANET-connectome development table.

KANET parameter	Neural substrates/ associated neural circuit	Initial circuit activation (Weeks)	Behavioral expression detectable (Weeks)	Gestational timing (functional expression window)	Functional significance	Ultrasound detectability	Postnatal correlation	Reference
Cranial sutures and head circumference	Fronto-parietal cortex, cranial mesenchyme, skull neuroanatomy	20–30	20–30	20–30	Structural proxy; complements behavioral measures	High (2D/3D)	Head growth, brain volume	[4, 7, 26]
Isolated limb movement	Corticospinal tracts, basal ganglia loops, cerebellum	20–22	20–24	20–32	Marker of voluntary motor circuit development	Moderate	Motor tone, movement symmetry	[1, 4, 10, 20]
Mouth opening/ yawning	Brainstem–cortical integration, sensorimotor cortex; orofacial sensory-motor loops	24–26	24–28	24–30	Sign of brainstem-cortical synchrony	High	Feeding, sucking reflex	[4, 5, 7, 26]
Facial movements	Facial motor cortex, brainstem (cranial nerve nuclei), subplate	24–26	24–28	24–28	Indicator of cortical–brainstem connectivity and emotional maturation	High (4D clarity)	Affective expression, social readiness	[4, 5, 8, 26, 28]
Eye blinking	Brainstem trigemino-facial reflex arc, reticular formation, supranuclear cortical modulation via thalamocortical network	22–24	24–28	24–28	Early sign of sensory gating and brainstem-cortical modulation	Moderate	Visual tracking, brainstem reflexes	[1, 4, 21, 24]
Hand-to-face movements	Somatosensory cortex, corpus callosum, interhemispheric tracts; cortical circuits for sensorimotor integration	24–26	26–30	24–28	Integration of sensory-motor and social-cognitive pathways	Moderate	Sensorimotor coordination	[1, 4, 8, 10, 20]
General movement quality	Thalamocortical loops, cerebellar feedback systems	24–26	26–30	24–36	Global neurological maturity index	High	General neurobehavioral integrity	[1, 4, 8, 24, 26]
Leg crossing/limb posture	Corticospinal and extrapyramidal tracts, corpus callosum	24–26	26–28	26–32	Assessment of postural control and bilateral integration	Moderate	Tone regulation, posture control	[1, 4, 8, 10]
Gestalt perception (behavioral personality)	Global network integration: limbic system, prefrontal cortex	28–30	30–34	28–36+	Overall integration of cognitive, motor & affective networks	Moderate–Low	Temperament, socio-emotional regulation	[1, 4, 8, 15, 20, 31]
Complex/variable movements (yawning, stretching, facial grimacing, trunk rotation, hand-to-mouth sequence)	Subplate network; brainstem & spinal pattern generators; emerging cortical integration	26–28	>28	>28	Reflects higher-order motor coordination and variability	Moderate	Maturity of integrated motor patterns	[1, 4, 26, 28, 29]

This table presents the neural substrates, developmental timing, functional significance, ultrasound detectability, postnatal correlation, and supporting references for each KANET, parameter. Reference numbers correspond to the citations in the manuscript's reference list.

Table 3: AI-Based KANET enhancements.

Study/Authors	AI method used	KANET parameter analyzed	Findings	Clinical readiness
Andescavage et al. [7]	Motion trajectory analysis using machine learning classifiers	Limb coordination, general movement	AI improves detection of subtle motion deficits	Experimental/ research stage
Jakab et al. [22]	Fetal MRI-based brain region segmentation with AI inference	Structural-functional mapping, behavioral emergence	AI modeling aligns brain maturation with sonographic signs	Semi-validated
Kim et al. [20]	Graph-based connectivity prediction from behavioral data	Asymmetry, movement entropy, eye/mouth events	Entropy metrics predict neuro-developmental age	Experimental
Bachnas et al. [34]	AI facial profiling from 4D ultrasound using CNNs	Facial gestures (smile, yawn, blink)	High facial recognition accuracy in fetal scans	Pre-clinical proof of concept
Andonotopo et al. [35]	4D facial expression tracking using temporal neural networks	Expression evolution from 24 to 36 weeks	Temporal expression maps match fetal age reliably	Early clinical phase
Andonotopo et al. [36]	Literature-based AI integration and algorithm classification	All facial parameters conceptually mapped	Potential roadmap for automated fetal behavior analysis	Conceptual/theoretical

Table 4: Comparison: KANET vs. fetal fMRI/DTI.

Criteria	KANET (4D ultrasound)	Fetal fMRI/DTI
Resolution (spatial/temporal)	Moderate spatial, high temporal	High spatial, low temporal
Motion sensitivity	Low-excellent real-time capture	High-motion artifacts common
Functional insight	Behavioral-level insight only	Direct neural network imaging
Cost and accessibility	Very low cost, widely accessible	Very high cost, limited globally
Standardization	High (KANET scoring protocol)	Variable, depends on center
Gestational window for use	22–36+ weeks	20–34 weeks (motion constraints)
Real-time behavioral observation	Yes (continuous capture)	Limited (snapshot-style)
Infrastructure requirements	Portable, bedside use	Requires MRI suite, sedation control
AI Compatibility	High potential (image/video ready)	Moderate (image analysis needed)
Clinical integration readiness	High in low-to-middle income settings	Primarily academic/research use

These relationships are synthesized in the KANET-Con, which maps each KANET parameter to a plausible neural substrate and its gestational onset. Table 2 extends this concept, showing how behavioral milestones align with circuit-specific maturation windows, while Figure 2 illustrates the conceptual mapping of behaviors to circuits, and Figure 3 presents a developmental timeline linking movement features to neurocircuit growth. Figure 4 highlights structural progression, including subplate dynamics,

thalamocortical wiring, and emerging cortico-cerebellar and interhemispheric pathways. Collectively, these data support the interpretation of fetal behavior as a functional proxy for neurocircuit maturation.

AI-based enhancements and comparative modalities

Four studies demonstrated the use of AI to enhance fetal movement and facial gesture analysis [34–36]. These systems applied convolutional neural networks and motion analysis algorithms to detect micro-expressions, evaluate movement entropy, and quantify symmetry, features often too subtle for consistent manual interpretation. AI-assisted analysis improved intra- and inter-rater reliability, reduced observer bias, and allowed creation of datasets for outcome prediction. Table 3 summarizes AI contributions to KANET scoring, including automated blink detection and gesture classification.

Comparisons between ultrasound-based functional assessment and MRI/DTI structural mapping (Table 4) highlighted complementary strengths: MRI provides high-resolution anatomical and connectivity maps but is limited by motion sensitivity and cost, while 4D ultrasound with KANET scoring delivers real-time, widely accessible functional information. The integration of AI into KANET scoring and risk stratification represents a workflow in which behavioral observation and computational interpretation converge to enable early neurodevelopmental screening. Figure 3 depicts a radial schema of connectome-behavior associations, emphasizing network-level rather than isolated motor interpretations.

Table 5: Cross-risk KANET application summary table.

Study/ Authors	Risk group	Sample size	Main finding	Altered KANET features
Fasoulakis et al. [17]	SARS-CoV-2 positive pregnancies	103 fetuses	KANET scores significantly lower in infected pregnancies; higher abnormality rate	Reduced facial expression, general movement quality
Dieb et al. [18]	Maternal hypothyroidism	52 pregnant women	Hypothyroid mothers had lower average KANET scores	Decreased movement variability, less facial activity
Bot et al. [19]	Monochorionic vs. Dichorionic twins	78 twins (MC/DC)	Significant neurobehavioral differences between MC and DC twins	Asymmetry in limb movement, delayed hand-to-face gestures
Kurjak et al. [12]	Multicenter high-risk pregnancy cohorts	2,750 cases across centers	KANET detects early abnormality in multiple high-risk categories	Facial, limb, and general movements most predictive
Miskovic et al. [25]	Various high-risk conditions vs. normal	110 fetuses	High-risk pregnancies had more borderline/abnormal KANET outcomes	More frequent absence of isolated movements, reduced mouth opening

The table presents a synthesis of key clinical studies applying the kurjak antenatal neurodevelopmental test (KANET) across a variety of high-risk pregnancy populations.

Global accessibility and clinical applications

KANET has been implemented in both high-resource and low-resource settings, including studies on gestational diabetes, hypothyroidism, intrauterine growth restriction, twin pregnancies, and maternal SARS-CoV-2 infection [17–19, 25]. These applications illustrate clinical versatility and the potential to extend neurofunctional screening beyond tertiary centers. Table 5 summarizes KANET application across diverse risk groups, with global accessibility patterns, scoring outcomes, and AI-enhanced 4D ultrasound examples described in the text.

Synthesis of optimal screening window

Across all modalities and analytic approaches, fetal behaviors reliably reflected underlying network development. Observations converged on the 24–32 week gestational window as optimal for neurobehavioral screening, corresponding to peak subplate activity, early corticospinal tract myelination, and interhemispheric integration [2, 3, 6–11, 21, 26, 28–30, 39]. KANET-scored behaviors within this window provide the clearest functional signal for identifying typical vs. atypical trajectories, supporting the clinical relevance of the **KANET-connectome matrix** and associated workflows.

Discussion

KANET overview

The KANET is a semi-quantitative tool designed to evaluate fetal neurobehavior using four-dimensional (4D) ultrasound. Originally developed to detect early neurological

dysfunction in high-risk pregnancies, KANET scores parameters such as facial expressions, spontaneous and isolated limb movements, blinking, and hand-to-face gestures [4, 5]. Figure 5 illustrates its structured scoring system, which differentiates normal, borderline, and abnormal findings and has facilitated global clinical adoption due to its accessibility, non-invasiveness, and ability to capture dynamic fetal behaviors in real time [12, 13, 25].

Multiple studies have linked KANET scores to postnatal neurological outcomes in conditions such as intrauterine growth restriction, gestational diabetes, maternal hypothyroidism, and SARS-CoV-2 infection [17, 18, 25, 26]. Table 5 summarizes these applications, including twin pregnancies where functional asymmetries have been detected even among genetically similar fetuses [19]. When interpreted through a connectomic lens, each KANET parameter reflects the maturation of specific neural systems, such as cortico-spinal tracts, basal ganglia, corpus callosum, and thalamo-cortical projections [6, 10, 22, 24], thereby reframing KANET as a functional neurodevelopmental interface rather than simply a movement-based assessment.

Fetal brain connectomics: key concepts

The fetal connectome describes structural and functional networks linking cortical, subcortical, and brainstem regions, which underlie sensory, motor, and affective behaviors [2, 3, 6, 9]. DTI and functional MRI have revealed early modular and small-world organization [7, 8, 11, 20, 21, 23]. Transient structures such as the subplate zone, active between 22 and 34 weeks, facilitate thalamocortical and cortico-cortical communication, supporting early sensorimotor integration [26, 28–30]. Emotional and social circuits, including the limbic system and prefrontal cortex, begin

KANET FETAL NEUROLOGICAL ASSESSMENT

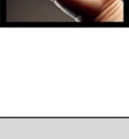
SIGN	ILLUSTRATION	SCORE		
		0	1	2
ISOLATED HEAD ANTEFLEXION		Abrupt	Small range (0–3 times of movements)	Variable in full range, many alternations (>3 times of movements)
CRANIAL SUTURES AND HEAD CIRCUMFERENCE		Overlapping of cranial sutures	Normal cranial sutures with measurement of HC below normal limit (–2 SD) according to GA	Normal cranial sutures with normal measurement of HC according to GA
ISOLATED EYE BLINKING		Not fluent (0–5 times of blinking)	Not fluent (0–5 times of blinking)	Fluent (>5 times of blinking)
FACIAL ALTERATION		(Grimace or tongue expulsion)	Not fluent (0–5 times of alteration)	Fluent (>5 times of alteration)
MOUTH OPENING		(Yawning or mouthing)	Not fluent (0–3 times of alteration)	Fluent (>3 times of alteration)
ISOLATED HAND MOVEMENT		Cramped	Poor repertoire	Variable and complex
ISOLATED LEG MOVEMENT		Cramped	Poor repertoire	Variable and complex
HAND-TO-FACE MOVEMENTS		Abrupt	Small range (0–5 times of movement)	Variable in full range, many alternations (>6 times of movements)
FINGER MOVEMENTS		Unilateral or bilateral clenched fist (neurological thumb)	Cramped, invariable finger movements	Smooth and complex, variable finger movements
GESTALT PERCEPTION OF GMS		DEFINITELY ABNORMAL	BORDERLINE	NORMAL
TOTAL SCORE		INTERPRETATION		
0–5		Abnormal		
6–13		Borderline		
14–20		Normal		

Figure 5: KANET fetal neurological assessment chart. This figure illustrates the structured evaluation system of fetal neurodevelopment using the kurjak antenatal neurodevelopmental test (KANET). Each assessed parameter, including head movements, eye blinking, facial expressions, isolated limb movements, and general movement quality, is scored on a scale from 0 to 2, based on the presence, absence, or complexity of fetal behaviors observed via 4D ultrasound. The cumulative score classifies fetal neurological status as normal, borderline, or abnormal. This assessment method is clinically significant as it facilitates early detection of potential neurodevelopmental issues and provides a standardized approach for interpreting fetal behavior as a reflection of neural circuit integrity. Note: figure reproduced from kurjak et al. (2008) with permission. The scoring definitions are as originally published. For clarity, observation duration for each parameter in KANET is typically 3 min, as described in the original validation studies.

showing specialization later in gestation [27, 31, 32]. Observable behaviors such as blinking, facial mimicry, and coordinated limb movements therefore reflect active neural network development rather than random motor discharge, positioning KANET within a modern systems-neuroscience paradigm.

KANET and connectome: timing and correlation

Fetal behaviors assessed by KANET emerge in predictable sequences linked to neural maturation. Facial expressions, blinking, and oromotor activity appear between 24 and 28 weeks, reflecting brainstem-cortical feedback and cranial nerve development [4, 5, 12, 26]. Limb coordination, hand-to-face gestures, and postural shifts parallel corticospinal, callosal, and basal ganglia maturation [6, 10, 22, 24]. Table 2 summarizes these relationships, while Figures 2–4 illustrate their timing and neural substrates. Disruptions in these coordinated developmental patterns have been associated with conditions such as autism spectrum disorder, cerebral palsy, and global developmental delay [15, 16, 33, 40]. The proposed KANET-Con organizes these findings into a unified interpretive framework [34–36].

Evidence for optimal time window

The gestational window between **24 and 32 weeks** consistently emerged as optimal for KANET application. This period encompasses peak synaptogenesis, axonal migration, and structural maturation of motor and sensory circuits [2, 3, 20, 24]. Network modularity and efficiency increase during this time, enhancing the interpretability of movement and facial expression patterns [8, 21, 23]. Beyond 32 weeks, behavioral expressiveness may decline as intrauterine space restrictions and evolving sleep–wake cycles reduce spontaneous motion variety [11, 24]. Thus, mid-second to early third trimester assessments provide the clearest behavioral insight into functional connectome development.

Clinical applications of the KANET-connectome framework

The KANET-Con improves interpretive precision, enabling early risk detection even when structural imaging is normal.

Examples include asymmetric limb movements linked to delayed corticospinal integration, reduced facial entropy in monozygotic twins, and blunted behavioral profiles associated with maternal SARS-CoV-2 infection [4, 6, 12, 17, 19, 22, 34, 35]. In resource-limited settings, where MRI is often unavailable, KANET provides a practical, low-cost method for neurofunctional screening [5, 8, 9, 25].

In clinical practice, the KANET–Connectome framework can be applied in a stepwise pathway:

- (1) **Prenatal screening** begins with routine obstetric ultrasound evaluation.
- (2) **Advanced image analysis** (including potential AI-assisted methods) processes ultrasound data to identify subtle neurobehavioral features.
- (3) **KANET scoring** quantifies fetal motor and facial patterns as markers of neurodevelopment.
- (4) **Risk stratification** categorizes findings into levels of concern, guiding the urgency of follow-up.
- (5) **Targeted interventions** are initiated when indicated, supporting early detection and timely clinical action.

Integration with AI-based analysis enhances reproducibility, supports systematic risk stratification, and offers scalability for population-level screening. This sequential approach links neurobehavioral assessment to underlying neural network maturation, ensuring that KANET findings are incorporated into broader prenatal care strategies.

Ethical considerations and global implications

Recognizing fetal behavior as an expression of functional neural integration raises ethical considerations regarding fetal sentience and identity [14]. As AI expands diagnostic sensitivity—detecting subtle facial asymmetry, movement entropy, and latency [34–36, 38]—protocol standardization, culturally sensitive counseling, and interdisciplinary oversight will be essential. Global disparities exist in access to advanced imaging; widespread adoption of ultrasound-based frameworks like KANET may help reduce inequities by democratizing prenatal neurofunctional assessment [39, 42].

Ultimately, viewing fetal behavior as a proxy for early neural connectivity highlights the need for interdisciplinary collaboration between fetal medicine, neuroscience, data science, and ethics to ensure these evolving diagnostic tools are applied responsibly.

Strengths, limitations and future directions

Strengths

This review proposes a conceptual shift in fetal neurodiagnostics by reinterpreting the KANET through the perspective of fetal connectomics. A key strength is its integration of multidisciplinary evidence, drawing from fetal MRI, diffusion tensor imaging, behavioral neuroscience, 4D ultrasonography, and AI. By synthesizing these domains into the proposed KANET-Con, the review provides a coherent framework that links specific fetal behaviors to the maturation of underlying neural circuits. Another strength is its methodological rigor. Although narrative in nature, the review adopted structured search and selection principles and critically appraised a diverse body of literature encompassing high-risk pregnancies, twin gestations, and maternal comorbidities. This breadth highlights the global scalability of KANET as a low-cost, non-invasive tool. Visual models, including developmental timelines and the KANET-Con, enhance interpretability and support translation into clinical practice.

Limitations

Several limitations should be noted. The proposed behavior-to-network associations are conceptual rather than empirically validated. Most available studies do not integrate prenatal imaging, KANET scoring, and long-term neurodevelopmental follow-up in the same cohort, limiting causal inference and the ability to define standardized diagnostic thresholds. KANET itself remains semi-quantitative and operator-dependent. Scoring variability—especially in subtle parameters such as facial gestures or limb asymmetries—can be influenced by examiner expertise, fetal position, gestational age, and maternal characteristics. Without standardized protocols or AI augmentation, reproducibility and consistency remain challenges. Additionally, heterogeneity in methodologies, sample sizes, and imaging platforms across the included studies limits the generalizability of findings.

Future directions

Future research should focus on prospective, multicentric studies integrating fetal connectome imaging, real-time behavioral assessment, and postnatal neurological outcomes. Such work is critical to empirically validate the

theoretical links proposed in this review and to develop predictive clinical models. Equally important is the refinement of AI-assisted tools capable of detecting facial entropy, blink variability, and movement asymmetry. These systems, once validated across diverse populations, could reduce interobserver variability and make fetal neurobehavioral screening scalable and objective. There is also a need for international consensus on optimal gestational windows for KANET application, threshold scores, and follow-up criteria. Standardized protocols would improve consistency across clinical settings and be especially valuable in resource-limited environments where advanced imaging is not available. Finally, as detection of early neurobehavioral deviations becomes more sensitive, ethical frameworks must evolve in parallel. Counseling strategies, communication protocols, and policy guidelines will be essential to ensure early findings are used constructively, avoiding overdiagnosis, parental anxiety, or unnecessary intervention. The future of fetal functional connectomics will rely on interdisciplinary collaboration among obstetricians, fetal medicine specialists, neuroscientists, ethicists, and technologists. The KANET-Connectome Matrix presented here provides a conceptual foundation for building integrated, ethical, and globally applicable approaches to early neurodevelopmental assessment.

Conclusions

This review presents a novel conceptual framework in fetal neurodiagnostics by aligning the KANET with the emerging science of the fetal connectome. By synthesizing 45 original studies spanning 4D ultrasonography, fetal MRI, diffusion-based imaging, and AI, we demonstrate that the behaviors assessed by KANET are not incidental motor events but functional signatures of developing neural circuits. Each observed parameter—facial mimicry, limb coordination, and general movement quality—corresponds to a distinct neurodevelopmental milestone within the architecture of the maturing brain.

Reframed through this lens, KANET evolves from a semi-quantitative behavioral checklist into a non-invasive, real-time diagnostic interface with the fetal brain. The proposed KANET-Con represents a conceptual leap: a framework enabling detection of network formation deviations well before postnatal symptoms manifest. This marks a shift in fetal medicine from late-stage detection to early-stage prediction and from anatomical observation to functional understanding.

The global accessibility of 4D ultrasound amplifies the clinical relevance of this model, supporting its adoption even

in resource-limited settings. When paired with AI-driven behavioral analytics, the potential emerges for observer-independent, scalable neurofunctional monitoring—transforming fetal assessments into predictive and preventive interventions. Challenges remain, including the standardization of behavior-to-network mapping, validation of machine learning tools, and integration of multimodal longitudinal datasets. Yet the convergence of behavioral science, neuroimaging, and systems neuroscience is already under way, demanding new disciplines, tools, and ethical frameworks.

The fetal brain is not a passive structure awaiting activation; it is already active, adaptive, expressive, and increasingly intelligible. KANET, viewed through the prism of connectomics, offers a means to listen more carefully—not only to how the fetus moves but to how the fetal brain thinks in motion. This review advocates for the formal emergence of a new discipline: fetal functional connectomics—a synthesis of imaging, behavior, and neuroscience with profound clinical applications, urgent ethical implications, and a wide-open scientific frontier.

Acknowledgments: The authors appreciate the Indonesian Society of Obstetrics & Gynecology (ISOG/POGI) and the Indonesian Society of Maternal Fetal Medicine (INAMFM/HKFM) for encouraging and supporting the work of this review article.

Research ethics: Not applicable.

Informed consent: Not applicable.

Author contributions: The authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Use of Large Language Models, AI and Machine Learning Tools: None declared.

Conflict of interest: The authors state no conflict of interest.

Research funding: None declared.

Data availability: Not applicable.

References

- Kostović I, Jovanov-Milošević N. The development of cerebral connections during the first 20–45 weeks' gestation. *Semin Fetal Neonatal Med* 2006;11:415–22.
- Thomason ME, Brown JA, Dassanayake MT, Shastri R, Marusak HA, Hernandez-Andrade E, et al. Intrinsic functional brain architecture derived from graph theoretical analysis in the human fetus. *PLoS One* 2014;9:e94423.
- Tymofiyeva O, Hess CP, Ziv E, Lee PN, Glass HC, Ferriero DM, et al. A DTI-based template-free cortical connectome study of brain maturation. *PLoS One* 2012;7:e35804.
- Kurjak A, Miskovic B, Stanojevic M, Amiel-Tison C, Ahmed B, Andonotopo W, et al. New scoring system for fetal neurobehavior assessed by three- and four-dimensional sonography. *J Perinat Med* 2008;36:73–81.
- Talic A, Kurjak A, Stanojevic M, Honemeyer U, Ahmed B, Miskovic B, et al. The potential of 4D sonography in the assessment of fetal neurobehavior: multicentric study in high-risk pregnancies. *J Perinat Med* 2005;33:63–9.
- Marguet F, Vezain M, Marcorelles P, Audebert-Bellanger S, Cassinari K, Drouot N, et al. Neuropathological hallmarks of fetal hydrocephalus linked to CCDC88C pathogenic variants. *Acta Neuropathol Commun* 2021;9:104.
- Andescavage NN, Du Plessis A, Murnick J, Brossard-Racine M, Vezina G, Limperopoulos C, et al. Complex trajectories of brain development in the healthy human fetus. *Cerebr Cortex* 2017;27:5274–83.
- Türk E, van den Heuvel MI, Benders MJ, de Heus R, Franx A, Manning JH, et al. Functional connectome of the fetal brain. *J Neurosci* 2019;39:9716–24.
- De Asis-Cruz J, Andersen N, Kapse K, Khirsnamurthy D, Quistorff J, Lopez C, et al. Global network organization of the fetal functional connectome. *Cerebr Cortex* 2021;31:3034–46.
- Song L, Mishra V, Ouyang M, Peng Q, Slinger M, Liu S, et al. Human fetal brain connectome: structural network development from middle fetal stage to birth. *Front Neurosci* 2017;11:561.
- Gao W, Lin W, Grewen K, Gilmore JH. Functional connectivity of the infant human brain: plastic and modifiable. *Neuroscientist* 2017;23:169–84.
- Kurjak A, Spalldi Barišić L, Stanojević M, Antsaklis P, Panchal S, Honemeyer U, et al. Multi-center results on the clinical use of KANET. *J Perinat Med* 2019;47:897–909.
- Moreira Neto R, Porovic S. Clinical study of fetal neurobehavior by the KANET test. *J Perinat Med* 2018;46:631–9.
- Stanojevic M, Zaputovic S, Bosnjak AP. Continuity between fetal and neonatal neurobehavior. *Semin Fetal Neonatal Med* 2012;17:324–9.
- Krontira AC, Cruceanu C. The fetal functional connectome offers clues for early maturing networks. *J Neurosci* 2020;40:4436–8.
- Scheinost D, Sinha R, Cross SN, Kwon SH, Sze G, Constable RT, et al. Does prenatal stress alter the developing connectome? *Pediatr Res* 2017;81:214–26.
- Fasoulakis Z, Kurjak A, Sapantzioglou I, Daskalaki AM, Daskalakis G, Antsaklis P. KANET evaluation in patients with SARS-CoV-2. *J Perinat Med* 2024;52:811–16.
- Dieb A, Salam R, Shaheen D, Shaeer E. Evaluation of foetal neurological behaviour in hypothyroid pregnant females—a pilot study. *J Matern Fetal Neonatal Med* 2019;32:2617–21.
- Bot M, Vladareanu R, Burnei A, Munteanu A, Calo I, Vladareanu S. Monochorionic vs dichorionic twins: Kanet test vs postnatal neurodevelopment. *Maedica* 2020;15:61–70.
- Kim JH, De Asis-Cruz J, Cook KM, Limperopoulos C. Gestational age-related changes in the fetal functional connectome. *Cerebr Cortex* 2023;33:2302–14.
- Taymourtash A, Schwartz E, Nenning KH, Sobotka D, Licandro R, Glatzer S, et al. Fetal development of functional thalamocortical and cortico-cortical connectivity. *Cerebr Cortex* 2023;33:5613–24.
- Jakab A. Developmental pathoconnectomics and advanced fetal MRI. *Top Magn Reson Imag* 2019;28:275–84.
- Zhao R, Sun C, Xu X, Zhao Z, Li M, Chen R, et al. Developmental pattern of individual morphometric similarity network in the human fetal brain.

- Neuroimage 2023;120410. <https://doi.org/10.1016/j.neuroimage.2023.120410>.
24. Wilson S, Pietsch M, Cordero-Grande L, Christiaens D, Uus A, Karolis VR, et al. Spatiotemporal tissue maturation of thalamocortical pathways in the human fetal brain. *eLife* 2023;12:e83727.
 25. Miskovic B, Vasilj O, Stanojevic M, Ivanković D, Kerner M, Tikvica A. The comparison of fetal behavior in high risk and normal pregnancies assessed by four dimensional ultrasound. *J Matern Fetal Neonatal Med* 2010;23:1461–7.
 26. Kostović I, Judaš M. The development of the subplate and thalamocortical connections in the human foetal brain. *Acta Paediatr* 2010;99:1119–27.
 27. Mrzljak L, Uylings HBM, Van Eden CG, Judaš M. Neuronal development in human prefrontal cortex in prenatal and postnatal stages. *Prog Brain Res* 1990;85:185–222.
 28. Kostović I, Judaš M. Transient patterns of cortical lamination during prenatal life: do they have implications for treatment? *Neurosci Biobehav Rev* 2007;31:1157–68.
 29. Kostović I, Sedmak G, Vukšić M, Judaš M. The relevance of human fetal subplate zone for developmental neuropathology of neuronal migration disorders and cortical dysplasia. *CNS Neurosci Ther* 2015;21:74–82.
 30. Judaš M, Sedmak G, Pletikos M, Jovanov-Milošević N. Populations of subplate and interstitial neurons in fetal and adult human telencephalon. *J Anat* 2010;217:381–99.
 31. Mulc D, Smilović D, Krsnik Ž, Junaković-Munjas A, Kopic J, Kostović I, et al. Fetal development of the human amygdala. *J Comp Neurol* 2024; 532:e25580.
 32. Šimić G, Krsnik Ž, Knezović V, Kelović Z, Mathiasen ML, Junaković A, et al. Prenatal development of the human entorhinal cortex. *J Comp Neurol* 2022;530:2711–48.
 33. Carroll L, Braeutigam S, Dawes JM, Krsnik Z, Kostović I, Coutinho E, et al. Autism spectrum disorders: multiple routes to, and multiple consequences of, abnormal synaptic function and connectivity. *Neuroscientist* 2021;27:10–29.
 34. Bachnas MA, Andonotopo W, Dewantiningrum J, Adi Pramono MB, Stanojevic M, Kurjak A. The utilization of artificial intelligence in enhancing 3D/4D ultrasound analysis of fetal facial profiles. *J Perinat Med* 2024;52:899–913.
 35. Andonotopo W, Bachnas MA, Dewantiningrum J, Adi Pramono MB, Stanojevic M, Kurjak A. AI and early diagnostics: mapping fetal facial expressions through development, evolution, and 4D ultrasound. *J Perinat Med* 2025;53:263–85.
 36. Andonotopo W, Bachnas MA, Dewantiningrum J, Pramono MB, Stanojevic M, Kurjak A. The capability of artificial intelligence algorithms to analyze and interpret complex medical data from four-dimensional ultrasound fetal facial imaging: a literature review. *Donald Sch J Ultrasound Obstet Gynecol* 2025;19:16–29.
 37. Brossard-Racine M, You W, du Plessis A, Vezina G, Limperopoulos C. Toward a more informative representation of the fetal-neonatal brain: a deep learning approach to characterize maturational changes. *Cerebr Cortex* 2023;33:10601–17.
 38. Yaqub M, Khan W, Alansary A, Bai W, Roy S, Bhogal A, et al. Brain volumetry and automated parcellation for 3D fetal MRI using deep learning. *Med Image Anal* 2023;87:102808.
 39. Bouyssi-Kobar M, Brossard-Racine M, Chang T, Mahdi E, Jacobs M, Murnick J, et al. Altered development of structural MRI connectome hubs at near-term age in preterm infants. *Neuroimage Clin* 2022;36: 103220.
 40. de Miranda DM, Ribas FT, de Castro Monteiro L, Fujita A, Furquim de Andrade CR, Vieira TC, et al. Prenatal exposure to air pollution is associated with structural alterations in the neonatal brain. *Environ Int* 2023;177:108061.
 41. Deprez M, Rousseau F, Makropoulos A, Schuh A, Kyriakopoulou V, Koch LM, et al. An automatic pipeline for atlas-based fetal and neonatal brain MRI segmentation. *Neuroimage* 2023;269:119972.
 42. Hughes EJ, Winchman T, Padormo F, Teixeira RPAG, Wurie J, Sharma M, et al. The developing human connectome project neonatal data release. *Sci Data* 2022;9:482.
 43. Andonotopo W, Bachnas MA, Dewantiningrum J, Pramono MB, Bernolian N, Yeni CM, et al. KANET at the crossroads of clinical practice and fetal neuroscience: a review of two decades. *Donald Sch J Ultrasound Obstet Gynecol* 2025;19:184–98.
 44. Pramono MBA, Andonotopo W, Bachnas MA, Dewantiningrum J, Sanjaya INH, Sulistyowati S, et al. Fetal neurobehavior and consciousness: a systematic review of 4D ultrasound evidence and ethical challenges. *J Perinat Med* 2025. <https://doi.org/10.1515/jpm-2025-0281> [Epub ahead of print].
 45. Andonotopo W, Bachnas MA, Dewantiningrum J, Pramono MBA, Sulistyowati S, Stanojevic M, et al. Integrating KANET and Doppler indices to predict neurodevelopmental delays in high-risk pregnancies. *J Perinat Med* 2025; 53:1000–13.